RESEARCH PUBLICATION No. 39

Review of the Crown-of-thorns Starfish Research Committee (COTSREC) Program

Dr Brian Lassig
Udo Engelhardt
Great Barrier Reef Marine Park Authority
PO Box 1379
Townsville Queensland 4810

Dr Peter Moran
Dr Tenshi Ayukai
Australian Institute of Marine Science
PMB 3, Townsville Queensland 4810

September 1995

A REPORT TO THE GREAT BARRIER REEF MARINE PARK AUTHORITY

ISSN 1037-1508
ISBN 0 642 23000 5
Published January 1996
by the Great Barrier Reef Marine Park Authority

National Library of Australia Cataloguing-in-Publication data:

Review of the Crown-of-thorns Starfish Research Committee
(COTSREC) Program.

Bibliography.
ISBN 0 642 23000 5.

1. Australia. Crown-of-Thorns Starfish Research Committee.
2. Crown-of-thorns starfish - Queensland - Great Barrier
Reef. 3. Crown-of-thorns starfish - Research - Queensland -
Great Barrier Reef. I. Lassig, Brian. II. Great Barrier
Reef Marine Park Authority (Australia). (Series : Research
publication (Great Barrier Reef Marine Park Authority
(Australia)) ; no. 39).

593.93

Great Barrier Reef Marine Park Authority

PO Box 1379
Townsville Qld 4810
Telephone (077) 81 8811

TABLE OF CONTENTS

TABLES

FIGURES

PREFACE

This review is intended as a reference document covering the scientific and administrative aspects of the Great Barrier Reef Marine Park Authority's crown-of-thorns starfish (COTS) Program and the Australian Institute of Marine Science's COTS Study from July 1989 to June 1995. The two organisations have worked together closely over the past ten years to monitor COTS outbreaks on the Great Barrier Reef and to understand the causes of starfish outbreaks. This document reflects the complementary and cooperative nature of these endeavours.

The review is sufficiently detailed to enable a full appreciation of the basis of the programs, their structure and operation, the status of projects, funding, the major outcomes of funded research, and future research directions.

The review complements two earlier reports that documented an earlier phase of COTS research involving the Authority and the Australian Institute of Marine Science from 1985 to 1989. At that time research was divided into ecological research and management-related research and separate reports were written for each of these two general areas. Moran and Johnson (1989) reviewed the former and Lassig (1991) the latter.

This review is a single volume, reflecting tighter integration of projects, an even greater level of cooperation between the organisations involved, and a stronger recognition that directed ecological research, while advancing scientific knowledge, provides critical information for management.

ABBREVIATIONS

AIMS	Australian Institute of Marine Science
BMR	Bureau of Mineral Resources
COTS	Crown-of-thorns Starfish
COTSAC	Crown of Thorns Starfish Advisory Committee
COTSARC	Crown of Thorns Starfish Advisory Review Committee
COTSREC	Crown-of-Thorns Starfish Research Committee
CRC	Cooperative Research Centre for Ecologically Sustainable Development of the Great Barrier Reef (abbreviated title CRC Reef Research Centre)
CSIRO	Commonwealth Scientific and Industrial Organisation
GBR	Great Barrier Reef
GBRMPA	Great Barrier Reef Marine Park Authority
ICLARM	International Centre for Living Aquatic Resource Management
JCU	James Cook University of North Queensland
NRIC	National Resource Information Centre
QDPI	Queensland Department of Primary Industries
R&M	GBRMPA Research & Monitoring Section
UQ	University of Queensland
VIMS	Victorian Institute of Marine Sciences

BACKGROUND

Review of the COTSAC Program

In December 1988, following criticism in the media of the Great Barrier Reef Marine Park Authority's handling of the crown-of-thorns starfish (COTS) issue, the then Minister for the Arts, Sport, the Environment, Tourism and Territories, Senator the Honourable Graham Richardson, requested a review of the Authority's crown-of-thorns starfish research program and policies. The research program had been recommended to the Authority by the Crown-of-thorns Starfish Advisory Committee (COTSAC), a body of experts convened by the Authority in 1984 for this purpose. Funding of $3 million over four years for the program (1985-86 to 1988-89) was provided by the Federal Government. The program was reviewed annually by another advisory body established by the Authority, the Crown-of-thorns Starfish Advisory Review Committee (COTSARC). Zann and Moran (1988), Moran and Johnson (1990) and Lassig (1991) have summarised the structure and results of this program.

The review for Senator Richardson was undertaken in January 1989 by Professor D. T. Anderson, Challis Professor at the University of Sydney. Terms of reference for the review were:

1. 'To review the Great Barrier Reef Marine Park Authority's present policy for managing the Marine Park in terms of the developing knowledge of the Crown-of-thorns Starfish and in particular the Authority's policy of limiting direct intervention to areas of special scientific or tourist interest.'

2. 'To review the adequacy of the mechanism for defining, reviewing and operating the Crown-of-thorns Starfish program.'

Anderson concluded that the research program had been defined, reviewed and operated in an efficient and productive manner and that the Authority's policy for crown-of-thorns starfish control (i.e. intervention only in areas of special interest to tourism or science) was soundly based, taking into account current knowledge of starfish populations on the Great Barrier Reef (Anderson, 1989). He recommended the program be continued for another three to five years at a dedicated and committed funding level of at least $1 million a year. He also recommended changes to the review committee to give that committee a more effective role in determining, in consultation with the Authority, the pattern of expenditure of these funds (see appendix 1). On 30 March 1989 Senator Richardson notified the Authority's Chairman, Professor Graeme Kelleher, he had accepted the recommendations of Anderson's report.

The Crown-of-thorns Starfish Research Committee (COTSREC)

Anderson recommended that Professor John Swan (who had chaired the COTSARC) continue as chairperson of the new advisory committee and that the committee include two representatives from the Great Barrier Reef Marine Park Authority (GBRMPA), two from the Australian Institute of Marine Science (AIMS) and three external experts. Professor Swan convened two meetings of an 'interim advisory committee' on 24 April 1989. He invited the Authority and AIMS representatives to determine Terms of Reference for the new committee (appendix 3) and to nominate additional members. Professor Ray Golding (Vice Chancellor of James Cook University of North Queensland) was invited to attend the second meeting later in the day to represent that institution (which had significant involvement in the previous research program). This meeting focused on allocation of residual funds for the current financial year. It was agreed the committee be called the Crown-of-thorns Starfish Research Committee (COTSREC).

Subsequently Professor Golding, Mr Robert Pearson (QDPI and former member of COTSARC), Dr Keith Sainsbury (CSIRO) and Professor Peter Davies (BMR, now University of Sydney) were invited to join the COTSREC. All four accepted the positions.

The full COTSREC first met in July 1989 in conjunction with a workshop organised to facilitate discussion on future directions in the crown-of-thorns research program. About forty scientists and managers attended the workshop. Discussion centred on current and future research in the areas of predation, terrestrial inputs and possible links with COTS outbreaks, geological studies to determine past occurrences of COTS, coral and starfish dynamics, recruitment, biology and controls. As well as convening workshops to review the status of knowledge in particular areas and to recommend further research needs, the Committee established a number of specialist working groups (see figure 1).

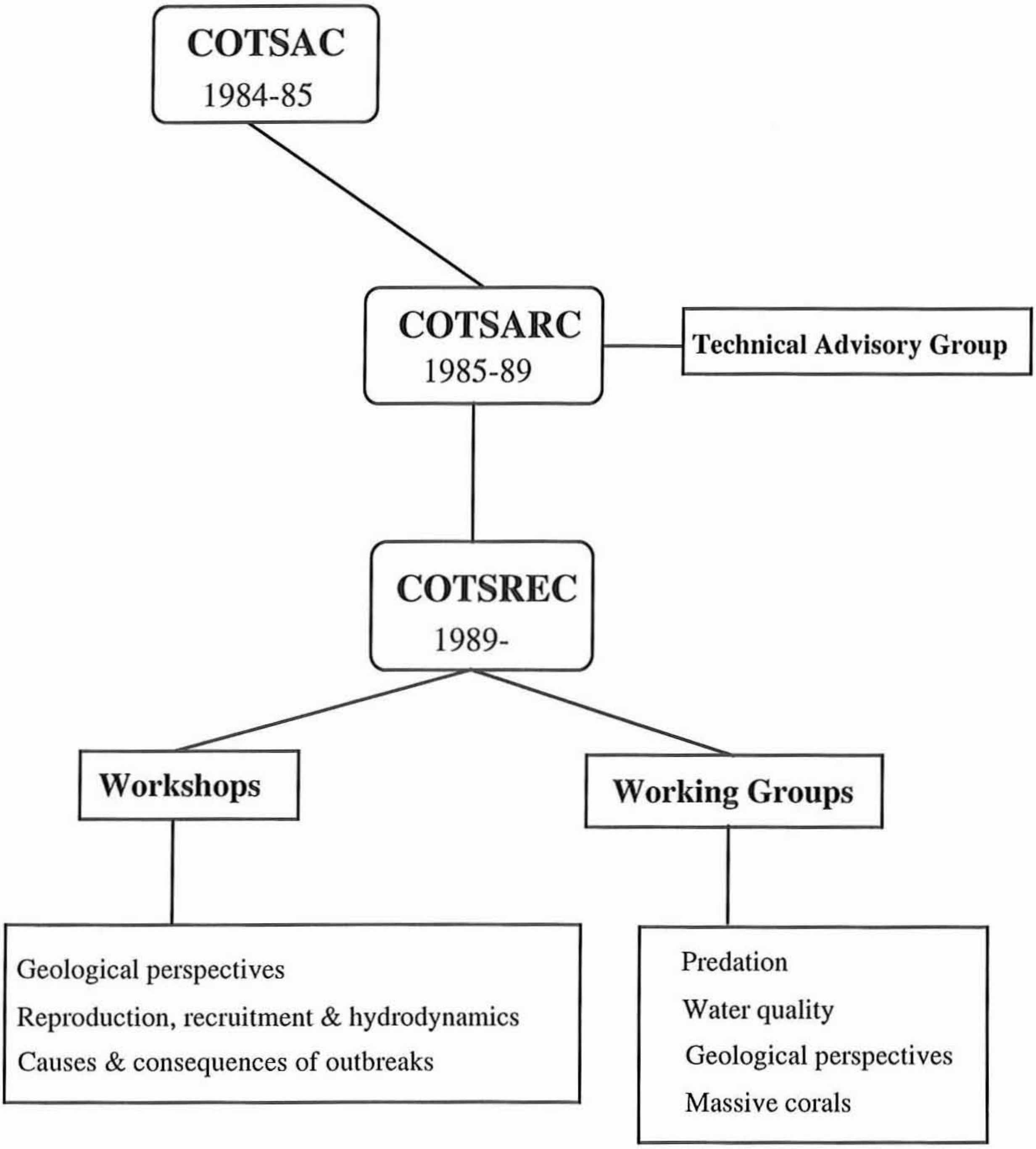

Figure 1. Review and program development processes used by COTS advisory committees

There have been a number of changes to the Committee membership since its establishment. For personal reasons Professor John Swan reluctantly relinquished his position as Chair of the Committee in January 1992 and was replaced by Professor Graham Mitchell (now Director of Research, CSL Limited; formerly Director, Royal Melbourne Zoological Gardens). Dr Meryl Williams replaced Dr Joe Baker when she was appointed as the new Director of AIMS in 1992. Dr Peter Moran was replaced by Dr Tenshi Ayukai because of increased commitments in other areas. Professor Peter Davies was replaced by Professor David Hopley (James Cook University of North Queensland) in mid-1993. Professor Chris Crossland (Director, CRC Reef Research Centre) joined the Committee in early 1994. Dr Peter Moran re-joined the Committee as Acting Director of AIMS following the departure of Dr Williams to take up an appointment as Director-General of ICLARM in early 1994. Dr Russell Reichelt was appointed Director of AIMS in early 1995 and AIMS representation on COTSREC is currently under review.

Since July 1989 the COTSREC has met twice annually - in April/May to develop recommended annual programs and in November/December to review progress.

The Availability of Funds and the Start of Research

In the August 1989 Federal budget it was announced that funds of $750 000 were to be provided for COTS research in 1989-90 and $1 million in 1990-91. In response to Professor Kelleher's seeking assurance of the third year of funding (as recommended by Anderson), Senator Richardson replied 'Although the Government's decision authorised funding for the program to 1990-91, I am happy for the Department and the Authority to operate on the basis that the program will continue into 1991-92. However, I would ask you that prior to entering the third year of the program, an assessment be carried out towards the end of the second year.' This assessment is described in the following section (Review of the COTSREC Program).

Funds for the first year of the program were made available to the Authority in August 1989. The COTSREC-recommended program of research was approved at the Marine Park Authority's meeting on 13 October 1989. Ministerial approval to enter into contracts involving payment of more than $50 000 (as required under S.56(a) of the Great Barrier Reef Marine Park Act, 1975) was granted on 9 November 1989.

All submitted proposals for funding which had not been peer reviewed previously were sent for review and returned to proponents for modification if required. Contracts were then drawn up with successful individuals and their institutions and the funds disbursed.

Many projects were thus not commenced until late 1989 or early 1990 (towards the end of the summer spawning and recruitment period for *Acanthaster planci*). The unavailability of suitable personnel for some projects resulted in delays of nearly twelve months. Dr Hugh Sweatman, the post-doctoral fellow appointed by James Cook University for crown-of-thorns starfish predation studies took up his position in September 1990.

Review of the COTSREC Program

In accepting the recommendations of Professor Anderson, Senator Richardson requested that the program be assessed after two years. This review was conducted by Dr R. E. Johannes, Senior Principal Research Scientist at the CSIRO Division of Fisheries in Hobart. Terms of reference for this review were:

1. 'To review the Great Barrier Reef Marine Park Authority's crown-of-thorns starfish research program with reference to the recommendations made by Professor D. T. Anderson in his 1989 report to Senator Richardson.'

2. 'To make recommendations on the provision of additional funds for the program.'

Appendix 4 lists the conclusions and recommendations arising from Dr Johannes' review. Dr Johannes recommended, inter alia, that the program be continued and this has occurred.

The Australian Institute of Marine Science (AIMS)

Professor Anderson noted that the facilities and expertise of the Australian Institute Marine Science were essential to the completion of crown-of-thorns starfish ecological research, but he highlighted a number of difficulties with the relationship between AIMS and the Authority. To overcome these problems, an Inter-Institutional Agreement was drawn up between the two organisations through the Australian Government Solicitor's office. The Agreement was established on 14 November 1989 and formalised aspects such as: the responsibilities of each institution and relevant personnel; reporting procedures; allocation of funds; ownership of capital equipment and research information; procedures for the disclosure of information; dealing with potential conflicts and the content of reports.

The Agreement has been updated each year to incorporate new or modified tasks (projects) for the successive financial years of the program. Progress reports for the majority of research tasks have been provided to the Authority by 30 April and 30 October each year.

While each Agreement contained a schedule for the payment of funds (quarterly in advance) a lengthy delay in funding was experienced at the beginning of the 1989-90 fiscal year (as discussed above). Some of the projects were on-going and funds were required to ensure the continuity of employment for staff. The Authority provided $75 000 (from unspent funds in the previous year) to cover expenses incurred during this hiatus in funding. Similar delays are experienced each year during the period of supply, prior to the Commonwealth Government's budget.

This delay in the provision of funds at the start of the COTSREC program led to certain projects being deferred as there were insufficient funds to employ new staff. Nonetheless, selection procedures were conducted during this period so that staff could be appointed once additional funds were received.

The first major payment of funds was made in early December 1989 enabling two additional research position appointments. Dr John Keesing, was appointed as a post-doctoral fellow to lead research into the survival of juvenile COTS and Dr Russ Babcock was appointed to lead investigations into the reproduction of the starfish.

Structure of the Research Program

The COTS Program operates as a sub-program within the Authority's Research and Monitoring Section. The budget for the Program, as a special Commonwealth Government fund between 1989 and 1992, was run separately to the Section's general budget. In 1992-93 funding for COTS research was incorporated into the Authority's appropriation. The Program is coordinated by the Program Coordinator who reports to the Director of the Research and Monitoring Section. The Coordinator liaises between researchers, their institutions and COTSREC members. Dr Leon Zann acted as the COTS Program Coordinator until December 1989, when he was succeeded by Dr Brian Lassig.

All research projects conducted by researchers at institutions other than AIMS are managed directly as individual projects by Authority staff employed through the COTS Program. Three staff managed the Program between 1989 and mid-1992. Staffing was reduced to two when Program funding was cut in mid-1992.

The conduct of projects is covered by legal agreements between the Authority, the researchers and their institutions. Agreements specify project execution details, allocation of funds, reporting schedules and responsibilities. Progress reports are scheduled to be submitted by researchers for consideration by the COTSREC at its biannual meetings.

The COTS research undertaken at AIMS operates as a sub-program of the Authority's program. Under the AIMS' terminology, the sub-program is referred to as a 'Study' and the individual projects as 'Tasks'. The COTS Study forms a discrete entity within the Reef Studies program. The Study consists largely of tasks funded by the Authority, but the Institute also provides substantial support (see table 2, page 66) and initiates some research tasks independently with Institute funds. Between 1989 and early 1993 Dr Peter Moran managed the AIMS COTS Study. During this time Dr Moran's commitments to the Reef-wide monitoring program and other institutional activities precluded his continuing in the COTS Study Manager's role. This was taken over by Dr Tenshi Ayukai in May 1993.

The COTS Study has included a variable number of tasks from year to year. Each task has a unique number that corresponds to that given in the main body of the Inter-Institutional Agreements (see table 3, page 67).

In 1990-91 AIMS received $800 000 p.a. from the Commonwealth Government for monitoring of the GBR. The funds provided to AIMS by the Authority for broad-scale surveys of COTS and corals (a major project funded through the COTS Program) were added to this independent funding to establish a long-term monitoring program that included more detailed surveys of benthos and fish as well as water quality sampling. From June 1993 the monitoring program was conducted through the then recently established Cooperative Research Centre for Ecologically Sustainable Development of the Great Barrier Reef (CRC Reef Research Centre) and AIMS was supported for this task through the CRC Reef Research Centre rather than by the Authority directly.

Within the AIMS COTS Study, each task has a Leader who is responsible for controlling the resources of that task as well as ensuring that the task objectives are completed as efficiently and effectively as possible. The Task Leaders report to the COTS Project Manager who is responsible for coordinating and managing the entire Study (including all research, personnel and resources). The Project Manager in turn reports to the Director of AIMS and liaises with the Program Coordinator at the Authority. This structure is currently under review.

The CRC Reef Research Centre has three main programs which each consist of four to six projects. Projects consist of a number of tasks. The Long-Term Monitoring conducted by AIMS is a task within the Inputs and Impacts Project which is a major component of the Regional Environmental Status Program. The CRC COTS Project consisted of six tasks in 1994-95. Each Task has a Chief Investigator and a User Contact (from management or industry). Program Leaders manage and coordinate tasks and projects and report to the Director of the Centre (Professor Chris Crossland). The Director reports to the Centre's Board.

PROJECT OUTLINES AND MAJOR RESULTS

This section provides a full description of projects supported through the COTSREC Program during the 1989-90 to 1994-95 financial years. Details of projects are as at 30 June 1995. Project titles marked with a '#' were undertaken as PhD research topics. The number of projects within the Program has reduced over successive years (see figure 2). This reflects both changes in funding and attempts to better focus on priorities while improving the quality of project management input. Projects are grouped into the following categories established by COTSREC in 1989 as priority research areas:

- Coral and Starfish Dynamics; Ecological Effects
- Larval and Adult Starfish Biology
- Geological Perspectives
- Controls
- Hydrodynamics, Recruitment and Terrestrial Inputs
- Predation

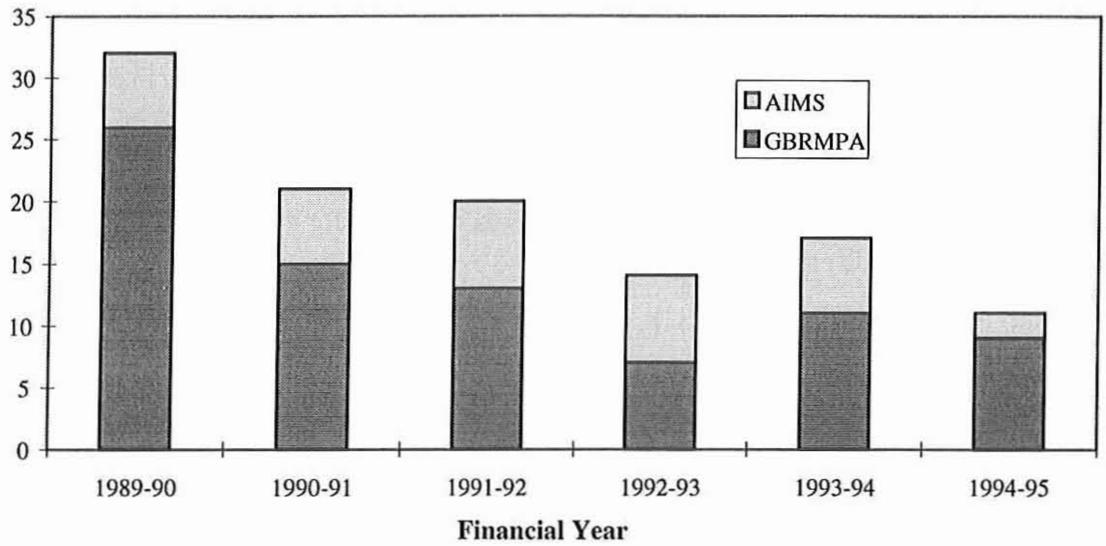

Figure 2. Number of projects within the COTSREC Program from 1989-90 to 1994-95

Reflecting the terms of reference of COTSREC pertaining to the provision of public information on the research program, several education and extension projects have been funded and/or conducted by Authority COTS Program staff. These are included under the heading 'Public Information'.

The Program contains a mix of short- and long-term projects. Longer term projects evolve and transform over time as needs change and as information accumulates. Objectives given in the project outlines are the original ones as defined in the Consultancy Agreement or Grant for the first year of the contracted research.

CORAL AND STARFISH DYNAMICS; ECOLOGICAL EFFECTS

Title An integrated study of hard coral regeneration and juvenile crown-of-thorns starfish at Green Island.

Investigator Mr D. Fisk (Reef Research and Information Services)

Objectives

(1) to provide quantitative and qualitative data on the nature of recovery of hard coral communities; and

(2) to search in detail in specific habitats where *A. planci* are predicted to occur and to provide correlative evidence of the importance of food availability and habitat type on settlement patterns.

Budget

1989-90	$23 000
1990-91	$27 430
1992-93	$23 000
Total:	**$73 430**

Status Project completed

Major Results

(1) By late 1990 coral cover in areas affected by large numbers of COTS in 1979-80 had increased dramatically, to the extent that competition among hard corals for space was occurring in some areas. The maximum hard coral cover recorded was 41% at one site; the average hard coral cover for thirteen stations was about 17.5%.

(2) Arborescent and plate *Acropora* spp. dominated the recovering community at all scales of investigation (spat, juvenile and adult colonies).

(3) In 1990 coral settlement on artificial plates showed no obvious pattern in available spat around the reef - there were no strong differences between fore-reef and back-reef sites and no differences between depths.

(4) In 1990 very low numbers of *A. planci* were recorded from intensive surveys for adult and newly settled starfish. The indications were that there had been low recruitment rates for the past few years and that individuals did not appear to be reaching sizes greater then 30-40 cm in diameter.

(5) Dramatic changes to some of the coral communities were detected in early 1993. Changes included large reductions in coral cover (over 30% reductions in some sites), significant reductions in the frequencies of arborescent and plate *Acropora* spp., and a significant increase in dead standing coral skeletons.

(6) The changes were attributed to three disturbances - a major cyclone in December 1990, localised predation by *A. planci* and *Drupella* spp., and effects of a form of black band disease.

(7) Survival of massive coral species was consistently higher than *Acropora* species at most stations. Massive coral species were numerically dominant at the majority of sites and were well represented at most of the remaining sites where they were not dominant.

(8) The reduction of total colony numbers occurred at a similar rate in all size classes, indicating that no significant size dependent mortality occurred.

(9) Coral larval recruitment had not increased in the permanent quadrats between 1990 and 1993, despite removal of much of the coral canopy.

Title	Broadscale surveys of the crown-of-thorns starfish and its effects on corals along the Great Barrier Reef (subsequently 'Long-term Monitoring of the Great Barrier Reef').
Investigators	Drs P. Moran and J. Oliver (AIMS)
Objectives	(1) to assess and summarise the broad-scale distribution and effects of the crown-of-thorns starfish since 1980; and (2) to develop a scientific understanding of the broad spatial and temporal dynamics of the crown-of-thorns starfish and its hard coral prey.

Budget

1989-90	$203 123
1990-91	$220 221
1991-92	$233 425
1992-93	$239 000
1993-94	$286 553
Total:	**$1 182 322**

Status Surveys incorporated into the Long-Term Monitoring Program being conducted through the CRC Reef Research Centre

Major Results

(1) Between 1989-90 and 1993-94 (March), a total of 320 reefs were surveyed throughout the Great Barrier Reef region using the manta tow technique. Of these, 98 reefs (about 31%) had been affected by outbreaks during the last episode.

(2) The activity of COTS slowly declined over the last five years, with the estimated percentage of reefs with active outbreaks declining from 16% in 1988-89 to 4% in 1992-93.

(3) COTS outbreaks nearly completed their southerly movements by 1993-94, with most of the reefs with active outbreaks being found in the Swain Sector at the southern end of the GBR.

(4) While the GBR system is recovering from the outbreak damage, a slight increase in COTS densities has been observed in a few of the northern sectors over the last two years.

(5) Analysis of outbreak patterns indicated that the likely epicentre for primary outbreaks is close to latitude 16°S. During the two observed outbreak episodes since 1960 outbreaks spread north and south from this area, the southward movement being faster and more extensive. Rates of movement for the southern 'drift' were as high as 80 km per year.

(6) The average time between outbreaks on reefs affected during both episodes was just under fifteen years - the frequently documented time for recovery of hard coral cover on reefs affected by COTS.

Title	Development of a robust method for determining the status of individual reefs with respect to outbreaks of crown-of-thorns starfish.
Investigators	Professor H. D. Marsh and Ms L. Fernandes (JCU)
Collaborators	Drs P. Moran (AIMS) and T. Done (AIMS)

Objectives

(1) to increase the robustness of the regression equations for estimating the proportion of crown-of-thorns starfish sighted during manta tow surveys;
(2) to quantify the biases associated with manta tow estimates of live and dead coral cover; and
(3) to use these results and the AIMS manta tow database to develop an unambiguous method of classifying individual reefs with respect to whether or not they are experiencing, or have recently suffered, major disturbance consistent with an outbreak.

Budget

1989-90	$11 500
1990-91	$27 889
Total:	**$39 389**

Status Project completed

Major Results

(1) Inaccuracies associated with manta tow estimates of live and dead coral cover were small.
(2) On average, less than 7.2% of the COTS on a reef are likely to be counted on a routine manta tow.
(3) The sightability of starfish at different sites was not confounded with density but varied with underwater visibility, individual reefs and individual observers. It is unlikely that the variability in sightability can be easily reduced on routine surveys, although a number of factors should be taken into account to minimise the biases and maximise the repeatability of manta tows.
(4) A decision making key and pro forma were developed to formalise the process by which reefs are classified with respect to COTS outbreaks.
(5) The manta tow technique is appropriate for estimating gross relative abundances of COTS and is therefore is a cost-effective method for determining broad-scale patterns of abundance.

Title Investigation of the trophodynamic implications of outbreaks of the crown-of-thorns starfish.#

Investigators Dr D. Klumpp and Mr T. Hart (AIMS)

Objective

(1) to assess the potential long-term effect(s) on populations of roving herbivorous fishes after a large outbreak of COTS, focusing on:

(a) density and biomass;
(b) feeding patterns;
(c) size at age and growth rates; and
(d) reproductive output of selected species.

Budget

1990-91	$13 500
1991-92	$16 000
1992-93	$15 000
1993-94	$20 200
Total:	**$64 700**

Status Draft Final Report (thesis) to be submitted late 1995

Major Results

(1) There were significant differences in both live coral and turfing algal covers between COTS impacted and non-impacted coral reefs.
(2) Despite a significant difference in availability of potential food resources there were no statistically significant differences in density, biomass, growth and feeding rates of roving herbivorous fish on impacted and non-impacted coral reefs.

Title

Impact of crown-of-thorns starfish on interactions among space occupants of coral reefs: predictive models of coral reef community structure.

Investigator

Dr C. Johnson (UQ)

Objectives

(1) to investigate the nature and outcomes of interactions among corals, coralline algae and turfs on 'healthy' reefs and reefs affected by COTS;
(2) to construct 'rules of assembly' from these empirical data (augmented by published work), and thence predictive spatial models (cellular automata) of dynamics of coral reef community structure for 'healthy' and affected reefs;
(3) to compare among model predictions and test their predictions at larger spatial and temporal scales than the scale at which empirical data were collected;
(4) to evaluate if biological interactions are important in structuring benthic reef assemblages, and if so, at what scales, and thus if the concept of 'assembly rules' is valid for coral reef communities; and
(5) to evaluate the utility of predictive models of community structure on coral reefs.

Budget

1990-91	$10 000
Total:	**$10 000**

Status

Project completed

Major Results

(1) Models of coral community recovery following COTS outbreaks indicate that the relationship between recovery rate and spatial extent of damage depends on the effective connectivity of the system (which affects availability of larvae for recruitment), and the relative magnitudes of larval retention (self-seeding) around individual reefs, background mortality rates of coral as well as the susceptibility of newly recruited corals to the disturbance.
(2) At high reef densities coral recovery rates are sensitive to survival of recent pre-damage recruits if coral life expectancy is relatively short (25 years), but the degree of self-seeding is relatively unimportant.
(3) If the density of reefs is low and there is no self-seeding, coral does not recover but either stabilises at reduced cover or declines, depending on its life expectancy (i.e. background rate of mortality).
(4) If reef density is low and there is some larval retention, then recovery depends largely on survival of pre-damage recruits and the rate of background mortality is less important.

Title	Analysis of coral colonies, populations and communities: interpretation of outbreak history and projection of recovery.
Investigator	Dr T. Done (AIMS)
Objectives	(1) to understand the significance of recent crown-of-thorns starfish outbreaks in relation to the population dynamics of coral communities, for the time period from present up to 200 years into the future; and (2) to resurvey sites to provide estimates of recruitment and survivorship of massive coral colonies, thereby improving the utility of previous model projections.
Budget	1989-90 $20 000 **Total: $20 000**
Status	Project completed
Major Results	(1) Recovery of hard coral populations on devastated reefs in the central GBR appears to occur as a southward moving 'front', lagging some years behind the front of *Acanthaster planci* populations which damaged the reefs in the first place. (2) This model is supported by the following observations: (a) coral cover was lower on the affected reef surveyed in the south compared with reefs in the north; and (b) in a number of abundant and fast and slow growing species (notably some *Acropora* and massive *Porites* spp.), colony sizes were larger in the north than in the south. (3) The regional scale patterns in coral cover and colony size appear to be reproduced on a local scale within reefs where large *A. planci* populations have had an extended period of residence.

Title	Use of near infra-red photography for monitoring effects of *Acanthaster planci* population explosions.
Investigator	Professor D. Hopley (JCU)
Objectives	(1) to monitor changes to the shallow reef areas exposed on extreme low tides on reefs previously affected by *Acanthaster* (Helix, John Brewer and Grub Reefs); currently affected reefs (Wheeler and Credlin Reefs) and reefs with the potential for infestation by *Acanthaster* (Davies Reef, etc.).
Budget	1989-90 $3 000 (final payment for project commenced in 1986-87 under the COTSARC Program) **Total: $3 000**
Status	Project completed
Major Results	(1) The techniques developed showed that valid high resolution digital data could be obtained from aerial photography. Ground-truthing of enlarged digital imagery demonstrated that the data are real and not the results of artefacts introduced during scanning.

(2) The project demonstrated that aerial photography, particularly when digitised, can be used to detect, map and monitor features not detectable on satellite imagery. However, considerably more developmental work, especially in conjunction with ground-truthing, is needed.

Title Surveys of benthic biota in the Cairns Section of the Great Barrier Reef Marine Park.

Investigators Dr B. D. Mapstone, Professor J. H. Choat, Professor H. D. Marsh (JCU) and Dr A. Ayling (Sea Research)

Objectives

(1) to determine the variation in abundances of the following taxa at several spatial scales:
- (a) large *A. planci*, massive poritid corals and giant clams;
- (b) benthic organisms and non-living substrata, with particular emphasis on live corals;
- (c) fish with medium to great mobility over short periods, including *Plectropomus* spp., lutjanids, chaetodontids, and possibly also some lethrinids, haemulids, scarids and labrids; and
- (d) fish with restricted home-ranges and relatively low mobility over short intervals, such as most of the pomacentrids and some labrids.

(2) to conduct detailed surveys of *A. planci* and coverage by living corals on reefs in the northern region of the Cairns Section of the GBR, specifically that region delineated by the Ribbon Reefs that is suspected of being the primary area of genesis of outbreaks; and

(3) to estimate the effects of GBRMPA zoning strategies on the abundances of the above organisms.

Budget

1989-90	$45 000	(plus $90 565 from R&M Section)
Total:	**$45 000**	

Status Draft Final Report being written, results used in design of fine-scale COTS surveys and other monitoring programs

Major Results

(1) Only fourteen COTS recorded during surveys of twenty-four reefs in the area.

(2) Most cost-effective transect survey method identified and now being used in the GBRMPA/CRC fine-scale surveys.

Title Crown-of-thorns and coral trout density on three Central Section reefs: 1983-1989

Investigators Drs A. M. and A. L. Ayling (Sea Research)

Objective

(1) to resurvey, six years after first being surveyed, three reefs affected by crown-of-thorns starfish to obtain information on starfish, coral trout and chaetodontid densities (as an indicator of coral condition) as well as hard coral cover.

Budget	1989-90	$6 090
	Total:	**$6 090**

Status Project completed

Major Results

(1) COTS had a major impact on coral communities on John Brewer and Lodestone Reefs in 1983-84, the starfish reaching densities of 200-260 per hectare at the peak of the outbreaks. The peak of starfish densities was short-lived, with numbers dropping to < 10 per hectare within nine months.

(2) Davies Reef did not experience an outbreak until mid-1989 with lower densities of starfish of 34-64 per hectare recorded at this time.

(3) Coral communities were beginning to recover on the reef front of Lodestone Reef by June 1989, six years after the COTS outbreak peak.

(4) The density of chaetodontids was dramatically affected by COTS outbreaks, with numbers on damaged reefs around 20% of those on unaffected reefs.

(5) There were no changes in coral trout density or length structure that could be attributed to the effects of COTS outbreaks.

Title Impact of the crown-of-thorns starfish (*Acanthaster planci*) on the community structure, demography and morphology of massive corals.#

Investigator Mr L. M. DeVantier (AIMS, UQ)

Objective

(1) to obtain precise information on the effects of predation by *A. planci* on the population structures of approximately one hundred species of massive coral.

Budget	1989-90	$18 000
	1990-91	$5 000
	1991-92	$4 000
	Total:	**$27 000**

Status Project completed

Major Results

(1) On reefs unaffected by COTS outbreaks, massive corals occurred at densities of up to 100 colonies per 100 m^2. Most colonies on these reefs had little or no injury (generally < 1/3 of their surface areas) despite the impact of cyclones and bleaching. Size-structures of most taxa on unaffected reefs were broad and dominated by adult colonies (> 20 cm diameter). Massive coral community structure was stable on these reefs for four years of the study.

(2) On most of the outbreak-affected reefs, predation by COTS at densities of > 200 starfish per hectare caused major short-term reductions in species richness and abundance. In the first three to four years following outbreaks, the affected assemblages had 1/3 to 1/2 the species and numbers of massive corals of comparable assemblages on unaffected reefs.

(3) Most surviving corals on the reefs affected by major outbreaks had sustained substantial injury to > 2/3 of colony surfaces. Highest levels of

injury and mortality occurred in small corals (< 10 cm diameter), particularly faviids of which up to 80% were killed.

(4) Classification of the sites in terms of the abundances and levels of injury of massive corals indicated that impacts of major COTS outbreaks overrode any effects related to reef geomorphology or cross-shelf location.

(5) Predation by COTS at densities of < 100 starfish per hectare had relatively little effect on assemblages of massive corals in comparison with other corals.

(6) Recovery of massive coral assemblages commenced within five years of major outbreaks, primarily from recruitment. Survival of remnants was of little importance for taxa other than *Porites* spp.

(7) On most of the outbreak-affected reefs, intense predation on many large colonies and subsequent colonisation of dead surfaces by a wide variety of corals resulted in fundamental changes in the structure of communities.

(8) There was little evidence of widespread injury caused prior to the 1960s on large massive corals on most reefs surveyed.

Title Green Island eastern shoals survey

Investigators Mr R. Pearson (QDPI), Dr B. Lassig and Mr U. Engelhardt (GBRMPA)

Objectives

(1) to revisit sites in the eastern shoal area of Green Island Reef where juvenile COTS were found in 1979-80, to record starfish numbers and coral condition; and

(2) to familiarise Great Barrier Reef Marine Park Authority staff with the type of reef substrate in which juvenile starfish were found on previous surveys so that they could be in a position to keep such areas under surveillance.

Budget

1993-94	$2 000
Total:	**$2 000**

Status Results to be incorporated into fine-scale COTS survey report for 1994-95.

Major Results

(1) There was no evidence of the eastern shoal area of Green Island Reef supporting a large population of COTS.

(2) Because of the very low hard coral cover and dominance of fleshy algae it is extremely unlikely that this area could support large numbers of COTS for quite a few years.

Title Fine-scale surveys of crown-of-thorns starfish (*Acanthaster planci*) in the Cairns Section of the Great Barrier Reef Marine Park.

Investigators Mr U. Engelhardt and Dr B. Lassig (GBRMPA/CRC)

Objectives

(1) to conduct an assessment of the current status of COTS populations on mid-shelf reefs in the suspected source area of previous outbreaks, and to

identify possible geographic (latitudinal) differences between populations;

(2) to identify a possible future outbreak during its early stages so that appropriate management strategies can be implemented in a timely manner;

(3) to assess whether or not pre-outbreaking populations of COTS exhibit characteristic habitat preferences that may assist in improving the cost-effectiveness of fine-scale surveys in the future; and

(4) to conduct a preliminary assessment of possible relationships between COTS abundance and (a) the incidence of coral scarring and (b) the amount of live coral available.

Budget

1994-95	$90 000	(funding from the CRC Reef Research Centre)
Total:	**$90 000**	

Status Surveys for 1994-95 completed, data analyses in progress. Project continuing.

Major Results

(1) There were pronounced latitudinal differences in the distribution of both juvenile and mature COTS, with reefs north of the Daintree area (ca. 16°S) generally supporting higher densities of COTS than reefs south of Port Douglas.

(2) Of the twenty-four mid-shelf reefs surveyed, two were classified as having active outbreaks, seven as having localised (spot) outbreaks (six of which are likely to develop into reef-wide outbreaks). Two currently non-outbreaking reefs are likely to have reef-wide outbreaks in the next 6-18 months.

(3) Reefs in the Lizard Island area are characterised by the presence of a substantial number of 2+ (juvenile) COTS. Unless this age class experiences high levels of mortality over the next 6-18 months, existing outbreaks are likely to increase and additional reefs in the area are likely to experience spot or reef-wide outbreaks.

(4) The situation on reefs off Cairns and south to Innisfail differs markedly from those to the north. Although a number of localised high density populations were found on reefs off Cairns, the starfish are generally more patchily distributed. A couple of reefs in this area appear to be supporting relatively high numbers of small juveniles (1+ age class).

(5) Generally, reefs south of Cairns had lower numbers of COTS and there were few signs of recent starfish recruitment.

(6) The relatively wide geographic spread of mature COTS (3+ and older starfish) throughout the northern parts of the Cairns Section indicates that the population structure observed is largely the result of regional rather than localised recruitment over several successive years.

Title The population dynamics of *Acanthaster planci* around Lizard Island, northern Great Barrier Reef.

Investigator Dr R. Stump (Consultant)

Objective

(1) to describe the characteristics and dynamics of the *A. planci* population at Lizard Island in terms of age structure, densities and distribution, growth

rates, recruitment rates, coral and starfish mortality rates, and starfish migration and movement.

Budget

1994-95	$36 645	(funding from the CRC Reef Research Centre)
Total:	**$36 645**	

Status Two field trips completed

Major Results

(1) Results show a regular pattern of recruitment over the past seven years. As a consequence, the population has a broad age structure, estimated between 14 and 146 months.

(2) Unless there is significant mortality in the 1+ and 2+ age classes over the next six to eighteen months, the fringing reefs of Lizard Island will support increasing densities of *A. planci*, a phenomenon not reported since the previous outbreak episode in the early 1980s.

(3) The increase in starfish numbers in the area is the result of consecutive recruitment events for approximately eight years. Together with the persistence of older individuals, ongoing recruitment has caused a slow build up in the spawning population. This pattern is likely to promote an increase in the size of future recruitment.

LARVAL AND ADULT STARFISH BIOLOGY

Title Age determination in *Acanthaster planci* (L.).#

Investigators Professor J. S. Lucas and Mr R. Stump (JCU)

Objective

(1) to assess potential methods of age determination in *A. planci:*

(a) pigment band counts and determination of cyclicity from mark and recapture exercises using tetracycline as a skeletal marker;
(b) accumulation of age pigment (lipofuscin) in pyloric caeca quantified from recaptured individuals; and
(c) skeletal and somatic morphometry.

Budget

1989-90	$33 750
1990-91	$41 000
1991-92	$21 200
1992-93	$6 900
Total:	**$102 850**

Status Project completed

Major Results

(1) Spine growth in adult *A. planci* is by elongation with addition of new stereom at the base, preserving growth history. Broad pigment bands develop parallel to the growth lines and are visible on ossicle surfaces after soft tissue removal.

(2) Field studies involving mark/recapture exercises, collection of morphometric data and analysis of growth indicated that these pigment bands can be used to determine age in sexually mature *A. planci* (i.e.

starfish aged 2+). A pigment band pair (light and dark band) is laid down each year.

(3) The *A. planci* population studied at Davies Reef in the central GBR consisted of four principal cohorts - two of which probably settled prior to an outbreak and two probably settled during an outbreak.

(4) The pre-outbreak group was generally larger in body size but produced relatively less gonad compared to post-outbreak individuals, indicating a lower reproductive effort.

(5) Sexual dimorphism in relative gonad size was accentuated in the post-outbreak group. In response to stress (such as depletion in food resources) during outbreaks, females draw more heavily on the body reserves causing resorption of soft body wall and skeletal tissues, reducing their lifespan to maintain a higher short-term reproductive effort. The corresponding male tactic promoted a relatively longer lifespan and higher fertilisation rates during the decline phase of the outbreak.

(6) A decrease in starfish body size over the study period directly followed a profound decline in coral resources. Mean asymptotic body sizes were lower in each successive cohort. It was concluded that the mode of growth varied between habitat-dependent determinate growth and plastic indeterminate growth.

(7) Results from additional studies of Western Pacific *A. planci* populations supported the theory that the life history strategy and morphology of *A. planci* are adaptable to prevailing conditions. It was concluded that the success of *A. planci* comes from its ability to vary the channelling of resources to the functions of growth, somatic maintenance and reproduction in response to environmental conditions.

(8) The development of this strategy implies that periodic outbreaks of *A. planci* occur under natural conditions.

Title Monitoring of recruitment of *Acanthaster planci* and community changes on Suva Reef and adjacent reefs, Se Vitu Levu, Fiji Group.

Investigators Dr L. P. Zann (GBRMPA) and Ms V. Vuki (University of the South Pacific)

Objectives

(1) to monitor annual recruitment of juvenile *A. planci* on Suva Reef;

(2) to monitor growth and mortality of the recruits (if any significant settlement should occur);

(3) to monitor adult populations for the onset of disease;

(4) to monitor changes which have occurred in designated cross reef transects; and

(5) to examine reef community structure in a selection of 'control' reef sites away from urban disturbances for subsequent monitoring.

Budget

1989-90	\$5 000
1990-91	\$4 000
1992-93	\$1 000
1993-94	\$1 000
1994-95	\$1 000
Total:	**\$12 000**

Status Project continuing

Major Results

(1) Annual recruitment of COTS over a thirteen year period in a known juvenile refuge substratum on Suva Reef was very patchy in time and space.
(2) A very low level of recruitment occurred in most years but three intensive, macroscale recruitment events occurred in 1977, 1984 and 1987; and two localised but intensive recruitment events occurred in 1982 and 1983.
(3) Growth rates within monitored cohorts were highly variable.
(4) Disease, attributed to an undescribed sporozoan pathogen, was responsible for two mass mortalities that resulted in the extinction of affected cohorts.
(5) There was no overt relationship between annual recruitment and rainfall events.
(6) In mid-1995, various parts of Fiji were experiencing moderate to serious COTS outbreaks. The majority of the populations were probably 3+ years old, settling in late 1991/early 1992. The major recruitment years of all four outbreaks recorded in Fiji since 1966 correspond with El Niño Southern Oscillation (ENSO) periods.

Title

Reproductive biology of the crown-of-thorns starfish.

Investigators

Dr R. C. Babcock (AIMS)

Objectives

(1) to obtain a more precise quantitative picture of the reproductive biology of *Acanthaster* populations during the spawning season;
(2) to obtain a more precise picture of starfish behaviour and reproductive biology during the spawning season based on field observations;
(3) to examine the role of pheromones in the aggregation and spawning behaviour of *Acanthaster;*
(4) to examine the effects of population density on reproductive seasonality and synchrony;
(5) to determine if there are latitudinal variations in the reproductive seasonality of populations in the central GBR and at the southern extremity of their distribution in the GBR region;
(6) to assess gamete viability in individuals of different nutritional states;
(7) to establish potential longevity of diluted sperm;
(8) to measure in situ fertilisation rates for artificially spawned starfish at varying densities and in differing conditions; and
(9) to determine in situ fertilisation rates for naturally spawning starfish.

Budget

1989-90	$40 417
1990-91	$105 727
1991-92	$116 850
1992-93	$33 000
Total:	**$295 994**

Status

Project completed

Major Results

(1) Direct observations of spawning behaviour and studies of the gametogenic cycle of *Acanthaster* populations at Davies Reef indicate that spawning activity peaks in early December. This pattern of peak

spawning early in the season is consistent with other observations on the GBR and elsewhere in the Indo-Pacific.

(2) The exact timing of reproductive events was not predictable, and spawnings were observed both day and night, and at various stages of the tide and times of the month.

(3) Spawning was observed until late January, but fewer starfish participated in these spawning events, and those that did were likely to have released fewer gametes than starfish spawning earlier in the season.

(4) Laboratory studies showed that eggs spawned after December had reduced levels of fertilisation, and more importantly, embryos were markedly less likely to develop successfully.

(5) The large number of gametes released by individual starfish allow populations to maintain high levels of fertilisation, even when separated by considerable distances. Fertilisation was still measurable even when spawning animals were separated by up to 100 m.

Title Feeding ecology of early developmental stages of *Acanthaster planci*. #

Investigator Mr K. Okaji (AIMS/JCU)

Objective (1) to investigate the feeding ecology and nutrition of larval and juvenile COTS.

Budget

1991-92	$20 500
1992-93	$23 515
1993-94	$32 841
1994-95	$28 920
Total:	**$105 776**

Status Thesis to be submitted in late 1995

Major Results

(1) COTS larvae reared in situ rearing chambers grew and developed normally. These results, however, were considered unreliable, as food levels in situ rearing chambers were elevated by inefficient flushing of water, algal fouling and contamination during handling of chambers.

(2) COTS larvae derive a significant proportion of their nutrition from phytoplankton in a relatively large size class (> 2 µm).

(3) COTS larvae can achieve their optimal development and growth rates above 0.75-0.80 µg chl. l^{-1}. Chlorophyll concentrations of this level rarely occur in GBR waters.

(4) Laboratory experiments with natural and food (cultured algae, natural phytoplankton, dissolved free amino acids) enriched waters suggested that the growth and development of COTS larvae were food-limited under natural conditions.

(5) Food availability does not seem to be a limiting factor in the development and survival of young juvenile COTS.

Title Assessing the role of dissolved organic matter and bacteria in the nutrition and energetics of *Acanthaster planci*.

Investigator	Drs T. Ayukai (AIMS) and O. Hoegh-Guldberg (University of Sydney)
Objective	(1) to determine the importance of dissolved organic material and bacteria in the nutrition and energetics of larval *Acanthaster planci*.
Budget	1991-92 $19 840 **Total: $19 840**
Status	Project completed

Major Results

(1) Heterotrophic bacteria (in a < 0.8 μm fraction) were not ingested by larvae, although utilisation of colony-forming and particle-associated bacteria remain to be investigated.
(2) Larvae were able to ingest two strains of photosynthetic cyanobacteria (approx. 1-2 μm in diameter). The clearance rates (volume of water cleared per animal per time) on these small phytoplankton, however, were more than one order of magnitude lower than those on larger ones (approximately 5 μm in diameter).
(3) Larvae were capable of taking up the amino acid, alanine, and the sugar, glucose. The uptake of glucose, however, was relatively low and appears unlikely to make a significant energy contribution to the metabolism and growth of larvae.
(4) Comparisons of the metabolic requirements of larvae and concentrations of DFAA and phytoplankton in the field indicate that growth and development of COTS larvae are likely to be limited by the availability of food resources.

Title Starfish larvae: identification and capture.*

Investigator Ms K. Roper (JCU)

Objectives

(1) to put together a collection of laboratory-reared and wild-caught larvae of different species of starfish;
(2) to develop a library of monoclonal antibodies with the aim of isolating one(s) that will react specifically to COTS, in addition to one(s) that react generally to asteroid larvae;
(3) to further the cross-screening of the existing monoclonal antibodies which were developed at Deakin University (raised against Japanese COTS bipinnaria);
(4) to develop a method of studying the temporal and spatial dispersion patterns of COTS larvae, using a specific identification system based on monoclonal antibodies; and
(5) to trial settlement tube traps as an alternative to plankton towing for the collection of planktonic and newly settled starfish larvae.

Budget

1991-92	$6 000
1992-93	$7 000
1993-94	$16 375
1994-95	$14 500
Total:	**$43 875**

Status Thesis to be submitted in late 1995.

Major Results

(1) Ten monoclonal antibodies that appear to react only with *Acanthaster planci* have been developed. These antibodies did not react with *Linckia laevigata, Choriaster granulatus* or *Culcita novaeguinea*, nor with a plankton sample unlikely to contain asteroid larvae.

(2) Of these ten COTS-specific antibodies, six reacted very strongly with Australian COTS material but reacted either very poorly or not at all to Japanese COTS.

Title Improvement of the rearing technique for the larvae and juveniles of crown-of-thorns starfish.

Investigators Dr T. Ayukai and Ms C. Cartwright (AIMS)

Objectives

(1) to improve rearing techniques for larvae and juvenile COTS; and

(2) to assess the effect of food limitation on the settlement competence and post-settlement survival of COTS.

Budget

1993-94	$61 833
1994-95	$87 320
Total:	**$149 153**

Status Project completed

Major Results

(1) A method for growing and maintaining coralline algae has been established. This will ensure continuity of food supply for young juvenile COTS in future years, reduce the mortality from predation by epifauna associated with coralline algae collected from the field, and greatly assist with sorting and counting juveniles for experimental work.

(2) Large numbers of COTS larvae and small juveniles produced for other projects (including larval biology, monoclonal antibody testing, juvenile feeding and predation studies).

(3) Draft manual for COTS rearing produced.

(4) Areas requiring further research (for both rearing and in relation to outbreak causality) identified.

Title Backup juvenile crown-of-thorns starfish rearing facilities.

Investigator Mr P. Hough (GBR Aquarium)

Objectives

(1) to provide a backup for the AIMS juvenile COTS rearing facility to lower the risk of high mortality experienced in previous years (especially in the month following settlement).

Budget

1993-94	$42 250
1994-95	$64 000
Total:	**$106 250**

Status Draft Final Report being written.

Major Results

(1) Ten larval batches produced seventeen million larvae, of which 3.7 million were cultured. Viability of eggs and larvae were more dependent on the female parent rather than the male parent.
(2) Survival rate from fertilised egg to one day post-settlement was 0.83%. Greatest larval mortality generally occurred between gastrula and late bipinnaria stages.
(3) Half of the batches were reared through to settlement. The mean settlement rate of competent larvae was 63.2%.
(4) Rearing temperatures significantly influenced the larval development period (nineteen days at 27°C; twelve days at 29.9°C).
(5) Survival rate from settlement to eight months of age was 1.7%.
(6) Mean diameter of juveniles increased 50% in the first thirty days. Arm generation was constant and rapid (one arm every fifteen days).
(7) Survival and growth of juveniles was food limited. Juveniles at higher densities (0.75 cm^{-2}) had lower mean body diameters than those at lower densities (0.25 cm^{-2}).

GEOLOGICAL PERSPECTIVES

Title *Acanthaster* feeding on coral reefs: the implications for bioerosion.[#]

Investigators Professor J. H. Choat and Ms B. Musso (JCU)

Objectives

(1) to investigate the dynamics and extent of degradation of the reef framework following predation by *Acanthaster planci*, specifically to:

- estimate the rates at which skeletons of three coral species are degraded by bioeroders;
- identify the major agents of bioerosion acting on freshly killed coral colonies and to quantify their relative contribution to the overall bioerosion;
- estimate levels of temporal and spatial variability of bioerosive processes within the reef crest environment;
- estimate long-term rates of internal bioerosion from areas of known past occurrence of COTS outbreaks and to compare them with long-term rates of bioerosion on reefs that have not been affected by COTS for the last 20 years; and
- detect changes in the species composition of bioeroding communities following COTS outbreaks.

Budget

1990-91	$15 000
1991-92	$18 000
1992-93	$15 000
1993-94	$6 850
Total:	**$54 850**

Status Thesis submitted

Major Results

(1) The extent of internal bioerosion in living coral colonies was small, but the agents responsible varied among the three coral species studied.
(2) The extent of colony bioerosion after twenty-one months following death differed greatly among coral species. The main bioeroders of dead corals were polychaetes, sponges and bivalves. Polychaete bioerosion was correlated with coral surface area; bioerosion by sponges and bivalves was correlated with coral colony volume.
(3) Changes in colony size decreased significantly with time over the twenty-one month period after colony death. The most rapid skeletal degradation occurred soon after death in *Acropora hyacinthus*, with wave exposure increasing the rate of colony degradation.
(4) The volume of calcium carbonate removed by internal bioeroders from dead colonies was significantly higher than the volume excavated from living colonies.
(5) In some acropore corals which dominate reef crest environments (particularly large plate-forming species such as *Acropora hyacinthus*), external bioerosion and degradation of dead corals was twenty times greater than that for internal bioeroders.
(6) In areas dominated by *A. hyacinthus*, mortality by *Acanthaster* results in substantial amounts of calcium carbonate being released into the reef environment in the short term. Large colonies of this species will be reduced by up to 50% of the size at death within nine months.
(7) Rates of bioerosion of dead massive *Porites* colonies sampled on reefs that had been affected by COTS outbreaks were not significantly different to those sampled on reefs that had not experienced outbreaks.
(8) In *Porites*, rates of internal bioerosion were 1-3 orders of magnitude lower than those found in *Acropora*.

Title Geological working group

Investigators Dr D. Kinsey (Chairperson), Drs P. Moran and J. Pandolfi (AIMS), Professor D. Hopley and Mr G. De'ath (JCU), Professor P. Davies (originally BMR, then University of Sydney), Dr B. Lassig (GBRMPA)

Objectives

(1) to recommend to COTSREC a research program that addresses the issue of crown-of-thorns skeletal elements in reef sediments as potential indicators of past population densities and outbreaks; and
(2) to initiate pilot studies to investigate potentially fruitful areas of research in this regard.

Budget

1990-91	$20 000
Total:	**$20 000**

Status Dr Kinsey retired, replaced by Professor David Hopley. Working Group meets on an ad hoc basis.

CONTROLS

Title Development of effective, environmentally friendly techniques for the local control of crown-of-thorns starfish.

Investigator Mr U. Engelhardt (GBRMPA/CRC)

Objectives

(1) to determine the minimum dose of copper sulphate required for effective local control of COTS; and
(2) to test other, more 'environmentally friendly' methods with a view to replacing toxic copper sulphate as the recommended poison.

Budget

1992-93	$4 000	
1993-94	$12 000	
1994-95	$12 750	(funding from the CRC Reef Research Centre)
Total:	**$28 750**	

Status Project completed

Major Results

(1) Experimental injection trials identified a minimum dose level of 4-8 ml of saturated copper sulphate ($CuSO_4$) required to kill mature starfish (approximately 30-40 cm in diameter).
(2) Results of control trials attempting to physically kill the starfish were inconclusive. Starfish that had been physically treated (i.e. cut into quarters or had the dorsal surface of their central disc opened up) showed a remarkable ability to survive. A relatively high proportion of the experimental animals was found to be alive sixteen days after treatment.
(3) Comparisons in the field of injection and physical damage techniques (cutting starfish into quarters) demonstrated that the latter are thirty to fifty times slower than injection and the risk of divers being spiked by spines is unacceptably higher.
(4) Experiments to identify an environmentally friendly alternative to copper sulphate injections demonstrated a suitable alternative - 100% sodium bisulphate (*'Dry Acid'*).
(5) The use of local vessels and expertise available in the Whitsunday area has resulted in a significantly higher profile and support for the COTS Program. The exercise has also served as a useful focus in facilitating direct communication and better understanding between tourism operators and Authority staff.

Title Local control technique manual.

Investigator Dr B. Lassig (GBRMPA/CRC)

Objectives

(1) to produce a manual that describes local COTS control techniques for use by permitted Reef-users.

Budget

1994-95	$1 500
Total:	**$1 500**

Status	Project completed; manual (entitled *Controlling crown-of-thorns starfish*) distributed on request and with approved local control permits.

Title	COTS Contingency Plan.
Investigator	Dr B. Lassig (GBRMPA/CRC)
Objectives	(1) to develop, with stakeholders, a plan of action to be implemented in the event of increasing crown-of-thorns starfish population densities on reefs of special interest to tourism or science.
Budget	1994-95 $1 000 **Total: $1 000**
Status	Project completed; booklet (entitled *Planning for crown-of-thorns starfish population increases*) distributed on request.

HYDRODYNAMICS, RECRUITMENT AND TERRESTRIAL INPUTS

Title	Anthropogenic influences on nearshore coral reefs, via mainland runoff, and correlations with spatial and temporal patterns in *Acanthaster planci* population explosions.#
Investigators	Ms C. Rasmussen and Professor D. Hopley (JCU)
Objectives	(1) to ascertain the exact effect of enhanced phosphate levels on coral colony growth; and (2) by way of a coring program commencing in the Cairns area, but then extending both north and south, indicate how the geochemical changes may have changed through time, and thus identifying a possible change in anthropogenic influences, particularly over the last one hundred years.
Budget	1989-90 $10 000 **Total: $10 000**
Status	Project completed
Major Results	(1) There was an association between land management practices of the Barron/Mossman River catchments and phosphate concentration of the adjacent rivers. (2) Very large quantities of phosphate in solution were transported through the river systems with most of the load delivered during flood events (approximately 90% in the 1988-89 wet season). (3) A direct correlation between marine phosphate levels and stream phosphate concentrations was not found, however a seasonal link between elevated levels of phosphate in marine waters and the use of agricultural fertilisers on the mainland was suggested. (4) There was a series of perturbations in the post-1950 chemical composition and morphological structure of a sample of *Porites* collected

from Green Island, an inner GBR reef. The perturbations in the skeletal porosity of the sample were similar to the those found in *Acropora formosa* colonies grown experimentally and exposed to varying concentrations of phosphate.

(5) The Green Island perturbations correlated with the use of fertiliser on the nearby mainland. Before the 1950s the pattern of chemical and morphological variation of this sample was consistent with patterns displayed by other inner- and inner/mid-shelf samples.

(6) Chemical and morphological variations in the skeleton of massive *Porites* corals are suitable for hindcasting paleoenvironmental conditions laid down in the skeleton at the time of precipitation.

Title Field surveys of juvenile crown-of-thorns starfish.

Investigator Dr P. Moran (AIMS)

Objective (1) to locate extensive, high density populations of juvenile crown-of-thorns starfish on reefs in the southern half of the Central Section of the Great Barrier Reef Marine Park.

Budget

1989-90	$11 000
Total:	**$11 000**

Status Project completed

Major Results

(1) Fourteen reefs between Townsville and Shute Harbour (Whitsundays) were surveyed for juvenile COTS.

(2) No high density populations of juvenile COTS were located through an effort of 192 twenty minute SCUBA swim searches at fifty-one sites involving a total of sixty-four diver hours.

(3) A total of twelve juvenile COTS were recorded, ranging from 5.5 cm to 15 cm in diameter.

(4) A number of small white coral 'feeding scars' were observed on all reefs surveyed. 53% of these were attributed to *Drupella*. Of the remainder, several other causative agents were suspected, in addition to juvenile starfish.

(5) The use of small coral 'feeding scars' as initial indicators of juvenile starfish activity was found to be unreliable, although the strategy and use of SCUBA swim techniques were considered appropriate for locating large populations of juvenile starfish.

Title Modelling approach to hydrodynamics and the large-scale larval dispersal of *Acanthaster planci*.

Investigators Dr M. K. James, Mr L. Bode and Mr I. Dight (JCU)

Objectives (1) to develop a database of digitised data, incorporating bathymetry, coastline, island and reef barriers and *A. planci* habitat;

(2) to develop software for (a) the automatic generation of computational grids at any desired spatial resolution and (b) the automatic generation of codes representing the sub-grid scale parameterisation of reef barriers;
(3) to conduct hydrodynamic simulations at a grid-scale of one nautical mile and to develop a method for handling the very large amounts of hydrodynamic information involved in larval dispersal simulations; and
(4) to investigate the consistency between the patterns of reef connectivity defined by larval dispersal simulations, and the database of COTS outbreaks.

Budget

1989-90	$36 000
1990-91	$30 000
Total:	**$66 000**

Status Project completed

Major Results

(1) A complete set of digital data now exists for the Cairns and Central Sections of the GBR Marine Park. Computer programs were developed which interpolate from randomly located digitised bathymetry data onto a regular grid of any desired scale.
(2) Sensitivity analyses of the hydrodynamic models showed that they are generally robust. Increasing the number of simulations, sampling density or number of particles representing the larval cloud produced similar patterns of connectivity.
(3) Broad-scale patterns of COTS dispersal resulting from model simulations were in agreement with observed spatial and temporal distributions of adult COTS populations as recorded on the AIMS database. At the scale of individual reefs, there was a trend for potential recruitment to reefs (as estimated by dispersal simulations) to be consistent with the observed presence of outbreak populations on those reefs. The consistency was stronger when data were integrated over geographic zones corresponding to cross-shelf position.
(4) Simulations of larval dispersal produced observed characteristics of COTS outbreaks on the GBR including:
- strong southward movement south of Cairns;
- neutral trend north of Cairns, with a weak northward movement in the far north;
- cross-shelf non-uniformity with outer matrix reefs seldom being exposed to competent larvae; and
- waning of outbreaks at the end of cycles as larval trajectories are confined to the main GBR lagoon.

Title The physical oceanography of the GBR during and prior to crown-of-thorns starfish outbreaks.

Investigator Dr K. Black (VIMS)

Objective

(1) to examine the available physical oceanographic data in relation to COTS outbreaks on the GBR throughout the known history of the starfish since 1981 and, in particular, during and prior to outbreaks to determine:
(a) currents;

(b) sea temperatures and salinities; and
(c) wind strengths and directions.

Budget

1990-91	\$13 500
1991-92	\$8 500
Total:	**\$22 000**

Status Project completed

Major Results

(1) Averaged over thirty years, the variation in temperature along the GBR between latitude 27°S to 11°S ranged from 25°C to 29°C. The 'optimum' temperature for maximum larval COTS survival (according to laboratory experiments) of 28°C occurs at 16°S, the latitude identified by other studies as the epicentre of initial outbreaks on the GBR.
(2) A suite of models were developed which can predict currents on the basis of coastal or offshore sea level differences. The models allowed hindcasting of currents over the previous twenty-five years.
(3) Analyses of the hindcast coastal currents revealed that self-seeding of the natal reef (or natal region) during periods of slow currents may be a critical factor causing primary outbreaks of COTS on the GBR. The dates of initial recruitment for primary outbreaks coincided with years when currents were slow throughout the pelagic dispersal phase.
(4) Some anomalies between the observed pattern of outbreaks and current predictions exist which suggest that some outbreaks to the south may have been primary, rather than secondary ones.

Title The movement of actual starfish outbreaks during the 1980s - unification of the oceanography and biology.

Investigator Dr K. Black (VIMS)

Objective

(1) to model the movement of COTS outbreak migration during the 1980s in the Central and Cairns Sections of the GBR using computer simulations of larval dispersal driven by real winds and currents.

Budget

1991-92	\$45 000
Total:	**\$45 000**

Status Project completed

Major Results

(1) A 25-year hindcast of currents on the GBR has been produced.
(2) The currents show that the excursions of starfish larvae may vary widely during each season and from one season to the next.
(3) Larval excursions due to currents were significantly correlated with the observed southward progression of starfish outbreaks.
(4) Currents were found to be exceptionally slow at the time of the suspected primary outbreaks in the 1970s, suggesting the possibility of exceptionally high recruitment to the natal reef or region at that time.
(5) A large-scale numerical model of the central GBR which fully assimilates the variations in low frequency currents due to coastal trapped waves and the East Australian current has been produced.

Title	Assessment of the utility of mitochondrial DNA as a genetic marker in crown-of-thorns starfish (*A. planci*).
Investigator	Dr J. A. H. Benzie (AIMS)
Objectives	(1) to establish methodologies for the extraction of mitochondrial DNA from crown-of-thorns starfish; and (2) to assess its utility as a genetic marker in the starfish.
Budget	1989-90 $4 000 **Total: $4 000**
Status	Project completed
Major Results	(1) Methods of assaying mitochondrial DNA (mtDNA) variation such as end-labelling that rely on the routine extraction of mtDNA from individual samples are impracticable because a strong nuclease degraded material rapidly. (2) The development of mtDNA or nuclear markers is promising where these rely on total DNA extraction and the use of either cloned probes or assaying variation from PCR amplified fragments. (3) The extraction of DNA of suitable quality from frozen specimens of pyloric caecae can be achieved. (4) mtDNA gene fragments from frozen samples can be amplified and cut with restriction enzymes.

Title	Assessing the utility of *Linckia* to test the connectedness of reefs with reference to *A. planci* dispersal.
Investigators	Dr J. Benzie and Ms S. Williams (AIMS)
Objective	(1) to assess the utility of *Linckia* to test the predictions of hydrodynamic models for larval dispersal of *A. planci* by: (a) establishing methods for detecting genetic variation in *Linckia*; and (b) assessing the level of genetic differentiation among *Linckia* populations.
Budget	1991-92 $5 500 **Total: $5 500**
Status	Project completed
Major Results	(1) Seven highly polymorphic allozymes show small differences in gene frequencies among populations of *Linckia laevigata*. Although minor, the patterns of differentiation suggest allozymes may prove useful in testing hydrodynamic models using *L. laevigata*. (2) Primers thought to span the highly variable D-loop region of the echinoderm mitochondrial genome have been successfully amplified in *L. laevigata* and promising results obtained from *A. planci*. These advances provide the most promising avenue to date for the development

of markers to trace dispersal among populations with high gene flow such as *L. laevigata* and outbreak populations of *A. planci*.

Title	Proposal to develop DNA markers for *Linckia laevigata* and *Acanthaster planci* to test hydrodynamic models and trace larval dispersal.
Investigators	Dr J. Benzie and Ms S. Williams (AIMS)
Objective	(1) to identify DNA variants for *Linckia laevigata* and *A. planci* with a view to testing predictions of hydrodynamic models for larval dispersal of *A. planci* by: (a) developing methods for detecting genetic variation in *L. laevigata* and *A. planci* mtDNA using PCR amplification; and (b) assessing the level of genetic differentiation among *L. laevigata* and *A. planci* mtDNA populations.
Budget	1992-93 $9 250 1993-94 $30 000 **Total: $39 250**
Status	Project completed
Major Results	(1) PCR amplification of mtDNA D-loop using the 12sa/16sb primer pair has produced very high yields of clean products, although some laboratory conditions, including the quality of water, remains to be improved. (2) A high level of diversity both within and among *Linckia* populations was detected in a preliminary screening by the restriction fragment length polymorphism analysis. (3) Although limited, preliminary data suggest that sufficient variation was observed that further studies should reveal whether or not reefs in different currents are genetically differentiated.

Title	Establishment of hydrodynamic model standards.
Investigator	Dr F. W. Wilkinson (Consultant)
Objective	(1) to assist the GBRMPA in the development of standards for the provision of modelling services for use in the management of the Great Barrier Reef.
Budget	1993-94 $15 000 (with additional funding from R&M) 1994-95 $15 000 (CRC funding with additional R&M funds) **Total: $30 000**
Status	Draft Final Report to be submitted late 1995.

Title	A preliminary study on the availability of dissolved organic matter to the nutrition of crown-of-thorns starfish larvae.
Investigator	Dr T. Ayukai (AIMS)
Objective	(1) to measure the spatial and temporal variations in availability of dissolved organic matter to the nutrition of the larvae of *Acanthaster planci* in the Cairns Region.

Budget

1992-93	$9 250
Total:	**$9 250**

Status Project completed

Major Results

(1) The concentration of dissolved free amino acids (DFAA) in the GBR shelf water between Port Douglas and Agincourt Reef was mostly below 0.1 $\mu mol\ l^{-1}$.

(2) The contribution of DFAA to the nutrition of COTS larvae is insignificant at relatively low DFAA concentrations measured. A further study is required as sampling periods did not coincide with the spawning season of COTS.

(3) The concentration of total dissolved nitrogen (TDN) cannot be used as an index of DFAA availability to COTS larvae, as DFAA are a minor component of TDN and no significant relationship was observed between these parameters.

Title	Significance of river runoff to the nutrient and plankton dynamics in the Cairns-Cooktown region: crown-of-thorns starfish perspective.
Investigator	Dr T. Ayukai (AIMS)

Objectives

(1) to resolve the spatial variability of temperature, salinity, light attenuation, dissolved inorganic nutrients, dissolved and particulate organic matter, microbial biomass and phytoplankton biomass and composition within the Cairns-Cooktown region;

(2) to resolve the short-term variability of cross-shelf distributions of temperature, salinity and basic water quality parameters in the area between Port Douglas-Agincourt Reef;

(3) to elucidate key processes that regulate the nutrient and plankton dynamics in the Cairns-Cooktown region with special emphasis on the river runoff of nutrients; and

(4) to develop an effective monitoring strategy for identifying the condition at the beginning of primary COTS outbreaks in the Cairns-Cooktown region.

Budget

1993-94	$8 548	(includes $4000 from GBRMPA Water Quality
Total:	**$8 548**	Program)

Status Project continuing with CRC support (see following project).

Major Result	(1) Coherence in the chlorophyll concentration between northern and southern transects was non-existent or very weak. (2) Geographic steering of currents plays an important role on the cross-shelf transport of riverine nutrients at certain locations in the Cairns-Cooktown region.

Title	Background and event-associated variations in concentration of dissolved free amino acids in the Cairns Section of the Great Barrier Reef Marine Park.
Investigator	Dr T. Ayukai (AIMS)
Objective	(1) to monitor dissolved free amino acids (a potential food source for COTS larvae) during the COTS spawning season to determine the significance of this food source to starfish larval survival under normal conditions and during periods of heavy terrestrial runoff.
Budget	1994-95 $30 000 (funding from the CRC Reef Research Centre) **Total: $30 000**
Status	Draft Final Report being written
Major Results	(1) Dissolved free amino acid (DFAA) concentration in the study area was consistently low (trace to 0.27 nmol), with no noticeable effects of time, space and freshwater discharge. (2) These results support the view that DFAA concentrations in the GBR lagoon are too low to make significant contributions to the nutrition of COTS larvae.

PREDATION

Title	The role of predation in factors influencing the survival of small juvenile *Acanthaster planci* cultured in the laboratory.
Investigator	Dr J. Keesing (AIMS)
Objectives	(1) to establish and operate a facility to rear large numbers of post-settlement *A. planci*; (2) to identify likely predators of small juvenile *A. planci* from field surveys of known habitats; (3) to undertake laboratory experiments on the survival of juvenile *A. planci*; (4) to conduct pilot experiments in the field on the survival of juvenile *A. planci*; and (5) to conduct detailed field experiments on the survival of juvenile *A.planci*.
Budget	1989-90 $67 271 1990-91 $93 639 1991-92 $94 800 1992-93 $89 000 **Total: $344 710**

Status Project completed

Major Results

(1) Techniques were developed for the rearing of large numbers of juvenile COTS.

(2) Small juvenile *A. planci* experience very high mortality rates due ostensibly to predation. The most important predators are thought to include crabs, shrimp and fish.

(3) Predation rates declined with age of the starfish, from 7.8% per day for newly settled starfish (0.5-1 mm diameter) to 2.5% per day at 3 mm and 0.8% per day at 13 mm (about six months of age).

(4) Spatial variability in mortality rates was very high, both within and between sites and habitats with no clear patterns emerging.

(5) Comparisons of mortality rates between juvenile *A. planci* and *Nardoa novaeguineae* of the same age (one month), under the same conditions in the field, showed that mortality rates of the latter were much lower (1.5% per day) compared to 8.6% per day for *A. planci*.

(6) Movement rates of juvenile *A. planci* in conditions of adequate food supply were very low.

(7) Preliminary results of a survey of the meiofauna inhabiting the extensive areas of coral rubble around reefs (the likely habitat of juvenile *A. planci*) suggest that this fauna is extensive. Densities of potential invertebrate predators of *A. planci* indicate that there is a very high predation pressure on very small *A. planci* in the field.

(8) Juvenile *A. planci* reared in the laboratory on different coral prey species grew at vastly different rates. Starfish reared on *Acropora* and *Stylophora* grew at the rate of 10-12 mm per month compared to just 0.1 mm per month in those feeding on *Porites* or coralline algae.

(9) The combination of results from predation, movement and feeding observations indicates that COTS must settle in areas of abundant food of the favoured type to survive. Starfish that settle in areas where food availability is poor grow slowly, thus prolonging the time spent at a small size vulnerable to predation.

(10) A pilot study to assess the suitability of settlement collectors for measuring settlement rates of *A. planci* in the field indicated that echinoderm larvae may be more abundant and have a more heterogeneous distribution than previously considered.

Title The status of *Acanthaster planci* in the south Pacific and selected groups in the Indo-Pacific.

Investigator Dr L. P. Zann (GBRMPA)

Objective

(1) to identify any commonalties among widely separated geographic areas which have been subjected to crown-of-thorns outbreaks, with a view to 'testing' the 'predator removal hypothesis'.

Budget

1989-90	$5 000
1990-91	$4 000
Total:	**$9 000**

Status Draft Final Report being written as a scientific paper.

Major Results

(1) The years of forty-nine COTS outbreaks or isolated aggregations were documented from thirty-one widely separated sites in the Indo-Pacific.
(2) Outbreaks were remarkably coincident in very widely separated areas in two oceans, closely corresponding to the periods of El Niño Southern Oscillation events (ENSO).
(3) Abundances of COTS during outbreak episodes (i.e. intensity of outbreaks) were moderately to strongly correlated with the total anthropogenic disturbances (population density, agriculture, fishing pressure and pollution levels).
(4) These results suggest that it is likely both natural events (ENSOs) and human influences affect the frequency and extent of COTS outbreaks in the Indo-Pacific.

Title Feeding studies on potential fish predators of post-settlement *Acanthaster planci*.

Investigator Dr H. Sweatman (JCU)

Objectives

(1) to examine stomach and intestinal contents of exploited fishes that feed on benthic invertebrates from reefs with high densities of *A. planci;*
(2) to conduct experimental studies on the digestive rates and gut transit times of lethrinids (potential *A. planci* predators);
(3) to determine what constitutes lethal damage to *A. planci*; and
(4) to determine the effects of sublethal damage on *A. planci*.

Budget

1989-90	$50 000
1990-91	$50 000
1991-92	$115 000
1992-93	$79 925
1993-94	$11 969
Total:	**$306 894**

Status Report being finalised.

Major Results

(1) Digested remains of adult and juvenile *A. planci* are easily recognised with the use of a dissecting microscope.
(2) The only systematically documented instance of predation by a lethrinid (one *L. nebulosus* had four arms from an adult *A. planci*) is not likely to have been fatal. It remains possible that several fish often attack the same starfish.
(3) Most (but not all) of the contents of a lethrinid's gut have been consumed in the preceding twenty-four hours. Thus, recording the number of *L. miniatus* with *A. planci* present in gut contents will give a slight (ca. 15%) underestimate of the number of fish that have consumed COTS in the previous twenty-four hours.
(4) Experiments removing arms from starfish have shown that, while effects of damage are variable, minor damage causes little mortality in the short term.

(5) While minor damage is not usually fatal, it does cause reduced gonad development by around 10%. There is evidence of reduced gonad size in damaged arms and arms adjacent to damaged arms in both sexes. This means that predators that inflict sub-lethal damage may lower reproductive output of *A. planci* populations.
(6) For control programs, even cutting a starfish in half was not reliably fatal.
(7) A concerted effort targeting lethrinids within a short distance of high densities of adult COTS found no evidence that *L. miniatus* prey on adults on the basis of a sample of ninety-five fish. Estimates of predation rates from gut samples are imprecise because they are themselves products of several estimates, leading to propagation of errors.
(8) Variation in gut fullness with time of capture suggested that *L. miniatus* do feed after dusk and so their feeding does coincide with times when juvenile *A. planci* would be out feeding on coral and hence accessible to predators.
(9) When juvenile *A. planci* were offered to lethrinids in aquaria no starfish were eaten.
(10) When juvenile *A. planci* were offered to lethrinids in the field, two species did eat some of them. However, this occurred in a minority of cases and in no instance were all the available individuals consumed. Starfish that were consumed were often bitten and spat out by several fishes before being swallowed. Lethrinids were unenthusiastic predators of juvenile *A. planci*.
(11) A predator exclusion experiment using juvenile *A. planci* in a site where putative predators were present found that total predatory mortality was very low relative to levels required by population models. Large fish predators could account for only a fraction of this predation. This did not support the hypothesis that commercially exploited fishes are important predators of juvenile *A. planci*.

Title The biology and ecology of the giant triton, *Charonia tritonis,* with particular reference to its role as a predator of the crown-of-thorns starfish *Acanthaster planci*.

Investigators Drs L. P. Zann and W. Gladstone (GBRMPA)

Objectives

(1) to investigate the behaviour (period of activity, refuges, searching and feeding) of *Charonia tritonis,* in aquaria and opportunistically in the field;
(2) to establish feeding rates of captive *C. tritonis* on *A. planci* and other asteroids in the aquarium;
(3) to monitor growth rates of the captive specimens over two years;
(4) to identify suitable field techniques appropriate for censusing *C. tritonis*; and
(5) to undertake pilot field studies to determine if a functional response exists between *C. tritonis* and *A. planci*.

Budget

1989-90	$10 000
1990-91	$5 000
Total:	**$15 000**

Status A total of \$3817 was expended over two years before the project was abandoned because of several logistical difficulties. These included locating sufficient numbers of *C. tritonis* and locating easily accessible reefs off Townsville with sufficient numbers of *A. planci* for feeding trials.

Title Modelling to assess the impact of predators on crown-of-thorns starfish populations.

Investigators Drs H. McCallum (UQ) and R. Bradbury (NRIC)

Objectives

(1) to develop and analyse models of the coral-starfish interaction in close association with field workers;
(2) to assist in the design of the experimental program by indicating which parameters associated with predation are of most impact in determining the effect of predators on COTS;
(3) to provide an indication of the level at which predation is likely to be of significance in the starfish-predator interaction, providing guidance on numbers of replicates required and sample sizes;
(4) to interpret the outcome of experimental studies and surveys and determine the consequences of observed results for starfish population dynamics; and
(5) after each stage of the field work, to refine models and provide guidance for the next step in the experimental program.

Budget

1989-90	\$23 037
1990-91	\$22 000
Total:	**\$45 037**

Status Project completed

Major Results

(1) It is not possible to establish a minimum level that predation must reach to be of importance to the prevention of either primary or secondary outbreaks. Any increase in starfish mortality may decrease the intensity or frequency of outbreaks.
(2) Any predator capable of increasing starfish mortality by 1% per day certainly would be of importance.
(3) Which aspect of predator behaviour is of most importance depends on whether primary or secondary outbreaks are being considered.
(4) For prevention of primary outbreaks, the searching behaviour of predators when starfish are rare is of primary importance.
(5) For prevention of secondary outbreaks, the maximum rate of prey consumption when starfish are abundant is the crucial parameter.
(6) Suites of predators of significance to primary and secondary outbreaks may be different.
(7) Lack of knowledge of the probability distribution of larval settlement and ignorance of mortality of juveniles unrelated to predation are major obstacles to investigating the potential impact of predation on juvenile starfish.
(8) Whilst COTS have the potential for chaotic behaviour, chaos appears unlikely for realistic parameter values. Unpredictable behaviour of

starfish populations is therefore most likely the result of stochastic factors rather than being intrinsic to the coral-starfish interaction.

(9) Predators appear to stabilise the coral-starfish interaction. Conversely, removal of predators can be expected to destabilise the interaction. Given chaos is unlikely, predator removal is likely to induce cyclical behaviour rather than throw the system into chaos.

Title Survey of marine scientists and other experts for anecdotal observations of crown-of-thorns starfish predation.

Investigator Dr B. Kettle (Marine BioLogic)

Objective

(1) to survey, by questionnaire, up to two hundred scientists and frequent reef-users working on Australian coral reefs, to document observed cases of *A. planci* predation.

Budget

1989-90	$2 000
Total:	**$2 000**

Status Project completed

Major Results

(1) A total of sixty-eight respondents that had dived and would have witnessed predation on COTS had an accumulated total of ca. 24 173 hours of diving on reefs with low density COTS populations and a further 5125 hours diving on reefs with high density populations.

(2) Twenty-six of the sixty-eight respondents (38%) had witnessed predation on COTS.

(3) A total of sixty-nine unique predation events were observed first hand, and one respondent reported a further thirty-one predation events which were assumed from fish gut contents inspection.

(4) Eight of the predation events reported were under unnatural conditions and excluded from further analysis, leaving ninety-two valid predation events.

(5) The giant triton, *Charonia tritonis*, was the most commonly observed predator, accounting for thirty-nine predation events (42% of all cases). Maori wrasse were responsible for seventeen events (18% of all cases), lethrinids for thirteen events (14% of all cases) and toadfish for eleven events (12% of all cases). Four other predators each accounted for one event and in eight cases the predator was not identified.

(6) Seventy-four percent of recorded predation events were from high density COTS populations suggesting that a predation event is witnessed approximately every seventy-five hours of diving on an 'outbreak' reef, whilst approximately 1013 hours of diving is required to witness a predation event on a 'non-outbreak' reef.

PUBLIC INFORMATION

Title	GBR Aquarium interactive display.
Investigator	Dr B. Kettle (Marine BioLogic)
Objective	(1) to develop an interactive display, based on an Apple Macintosh computer, to provide public information on the crown-of-thorns starfish, the research program and management issues.
Budget	1989-90 $6 000 1990-91 $6 000 **Total: $12 000**
Status	Project completed

Title	'Blue Book' Research Update 1991-92.
Investigators	Dr B. Lassig and Mr U. Engelhardt (GBRMPA)
Objective	(1) to update the 1987 Australian Science Magazine COTS issue.
Budget	1991-92 $5 000 **Total: $5 000**
Status	Project completed

Title	Crown-of-thorns starfish Video Update.
Investigators	GBRMPA and AIMS
Objective	(1) to produce a COTS video with recent results from research, updating the one produced by GBRMPA in 1987.
Budget	1990-91 $5 000 1991-92 $2 000 **Total: $7 000**
Status	Project completed

Title	Reef-user COTS sighting database.
Investigator	Mr U. Engelhardt (GBRMPA)
Objective	(1) to establish and maintain a database to record completed Reef-user COTS sighting forms.

Budget	1993-94	$2 000	
	Total:	**$2 000**	

Status Database established and backlog of completed returns input. Project continuing.

Title Education/extension program.

Investigator Mr U. Engelhardt (GBRMPA/CRC)

Objectives

(1) to provide up-to-date, relevant information on progress and developments in relation to the COTS phenomenon to members of the general public, the media and Reef-user groups;
(2) to get Reef-users actively involved in a revised COTS survey scheme; and
(3) to identify and address the particular educational needs of teachers and students at both upper primary and secondary schools involved in marine environmental studies.

Budget	1993-94	$8 000	
	1994-95	$11 000	(funding from the CRC Reef Research Centre)
	Total:	**$19 000**	

Status Revised survey scheme (COTSWATCH) launched in November 1993. Unprecedented numbers of completed survey forms received. Informal discussions with secondary school teachers and school librarians have identified important attributes to be incorporated into any future publications. Six-monthly updates/lectures are being presented in the major regional centres along the Queensland coast, targeting QDEH and tourism industry staff.

OVERVIEW OF PROGRAM AREAS

This chapter presents an overview and interpretation of results of projects in each of the priority research areas established by COTSREC. The final section 'The Possible Causes of Outbreaks' integrates results across research areas to describe the current state of knowledge on this critical objective of the Program.

Coral and Starfish Dynamics; Ecological Effects

This is a relatively diffuse area of the COTS Program, encompassing several major approaches at a variety of scales. Projects have focused on five major issues:

- broad-scale patterns of COTS distributions and their effects on the GBR;
- fine-scale distribution and abundance of COTS on mid-shelf reefs in the Cairns Section of the Great Barrier Reef Marine Park;
- the impact of outbreaks on coral communities and the dynamics of recovery;
- development and refinement of techniques for monitoring COTS and their effects at broad- and fine-scales; and
- the impact of outbreaks on fish communities.

Broad-scale (Reef-wide) Patterns of Outbreaks

Outbreaks moved through the Townsville and Cape Upstart Sectors in the late 1980s and by the early 1990s were confined largely to the Swain Reefs at the southern end of the GBR. COTS populations in the Swain Sector are considered to be independently derived from those elsewhere on the GBR (Moran et al. 1992). The recent episode, which was first detected at Green Island in 1979, ostensibly finished in the early 1990s.

Annual broad-scale surveys have provided critical information to address uncertainty (and debate) over the extent of damage to the GBR from COTS outbreaks. The surveys established that 17% $\pm$ 4% of reefs have been affected by outbreaks in the recent episode. This equates to between about 370 and 600 individual reefs.

The surveys found that impacts on individual reefs were highly variable. In the recent outbreak episode approximately 57% of reefs with outbreaks had moderate to high coral mortality over at least a third of their perimeters. About 10% of affected reefs had high coral mortality (> 50%) over most of their perimeters. On average, outbreaks produced a 3.4 fold increase in the levels of dead coral cover on reefs (Moran et al. 1991). A comparison of records of affected reefs from the two recent outbreaks revealed that 35 reefs had experienced outbreaks on both occasions. The average time between the two episodes on these reefs was 14.68 years (Moran et al. 1992), which is consistent with earlier research that showed reef recovery (at least in terms of coral cover) may take from 12-15 years (Moran 1986).

Reconnaissance surveys using the manta tow technique have provided a framework for the detection and interpretation of COTS outbreak patterns on the GBR. From the relatively limited information on the previous episode that is available, it appears that the overall patterns and characteristics of the two episodes were very similar. Both apparently originated north of Green Island close to latitude 16°S, spread predominantly to the south over the next 12-14 years before waning to the north of the Pompey Group at about latitude 21°S. Hydrodynamic processes can explain the latitudinal locations of both the origin and the waning of previous outbreaks on the GBR. These are discussed in the following sections 'Hydrodynamic, Recruitment and Terrestrial Inputs' and 'The Possible Causes of Outbreaks'.

While the patterns of outbreaks during the two observed episodes on the GBR appear to be consistent, there are no available comparative data to assess the relative extents or severity of the two episodes.

Results from the broad-scale surveys have provided input information as well as correlative and corroborative evidence for other research, in particular modelling of larval dispersal (see section on 'Hydrodynamics, Recruitment and Terrestrial Inputs') and coral recovery.

Fine-scale Distribution and Abundance of COTS in the Cairns Section

Because neither of the two previously recorded COTS outbreak episodes on the GBR were anticipated or planned for (and perhaps because coral reef monitoring was not in vogue at the time), there is a dearth of information on the dynamics of COTS populations leading up to those outbreaks. Both episodes were first observed as outbreaks on frequently visited Green Island reef. Subsequent surveys of surrounding reefs found that many of these also supported outbreaks. Computer modelling of the last outbreak suggested that the observed outbreaks at Green Island and surrounding reefs were secondary, derived from primary outbreaks to the north, probably behind the Ribbon Reefs at around 16°S latitude. The geographic spread of the original source of outbreaks and the dynamics of the population increases are unknown. There has been some debate as to whether or not the outbreaks resulted from a single extraordinarily good year of recruitment or a series of relatively good years. Determining the spatial scale of primary outbreaks is vital to understanding the causes of outbreaks and in developing appropriate management responses.

The recent fine-scale surveys in the Cairns Section and a closer study of the COTS population at Lizard Island were initiated to address this need. The surveys show that COTS populations are increasing virtually simultaneously on mid-shelf reefs covering a wide geographic area, from about 14°30'S to 16°S. Current high density populations appear to have resulted from a series of good years for COTS recruitment, not a single massive recruitment event. The wide spread of COTS ages represented in the population at Lizard Island indicates that recruitment on that reef has been consistently high for the past seven to eight years.

Because of the relatively large number of COTS juveniles present on many reefs, it is likely that COTS populations will increase in the area over the next year or so. However, only time will tell if the observed build up is the start of another major outbreak episode.

The major difficulty in making projections from the current situation is the lack of comparable detailed information on COTS populations prior to the previous two outbreaks. On these occasions the first comprehensive surveys in the Cairns Section were undertaken one to four years after the outbreaks were first detected at Green Island. Although the outbreaks were first detected at Green Island, it is possible these were secondary, being derived from earlier primary outbreaks to the north. The first significant spawning of COTS is at three years of age when they also become conspicuous (because of their size and feeding activity). So the origin of the episode may have actually been six or more years before the outbreak was detected at Green Island and seven to eleven years before surveys were conducted. In the absence of regular (annual) monitoring, the start of many outbreaks has been 'guesstimated' (and unfortunately little supportive evidence published).

A variety of techniques (manta tow, spot checks and swim searches) and survey units were used in the earlier surveys. In those days before GPS and the Reef Gazette, reefs were occasionally confused and published locations ambiguous. Some survey data were aggregated into such broad categories as to defy meaningful ecological interpretation. A lack of consistent definitions of outbreaks compounds the confusion.

Although the broad picture of outbreak patterns is fairly consistent, comparisons on finer (reef) scales of resolution are problematic. Currently, COTS populations on reefs off Cairns are generally less dense and more patchy compared to those in the north of the Section. In the previous episodes, outbreaks were detected on reefs off Cairns first. This chronological difference might reflect the earlier initiation of monitoring this time compared to previous episodes or the wider spread of tourism operations rather than ecological phenomena.

The other major element contributing to the vagarity in forecasting from the current situation is the lack of hydrodynamic data for the area. The Ribbon Reefs appear to form an effective barrier to the South Equatorial Current, minimising the functional impact of the East Australian Current (EAC) in the lagoon and reef matrix. While the EAC has been monitored for the past seven years, currents inside the Ribbon Reefs have not. Currents in the mid-shelf region are probably wind forced and as a result, highly variable. Given the variability in summer wind velocities (and the presumed current velocities) as well as uncertainty over the exact spawning times of *Acanthaster planci*, larval transport distances and directions are unpredictable.

Impact on Corals and Recovery

Several projects have addressed the impacts of COTS outbreaks from finer scale perspectives. Monitoring of benthic communities on Green Island Reef since 1986 has provided a unique dataset on detailed recovery patterns following the outbreak in 1979-80. Recovery proceeded according to the generally recorded pattern for the first ten years with arborescent and plate *Acropora* spp. dominating and competition among hard corals occurring as coral cover approached pre-outbreak levels. During this time COTS recruitment and adult density remained low. Dramatic changes to some communities occurred over the next three years with > 30% reductions in coral cover at some sites. Because of the infrequent nature of the surveys the changes could not be attributed to particular causes, however cyclones, localised predation by COTS and *Drupella* spp. as well as disease are likely factors (Fisk 1993). This study highlighted the synergism between a number of stresses to corals that may influence theoretical recovery trajectories.

Computer modelling has also provided valuable insight into variability in recovery following outbreaks and the interaction or balance of determining factors. Models indicate that recovery may depend on a range of variables including the spatial extent of damage, intensity of damage on individual reefs, connectivity between reefs, the degree of self-seeding and life history characteristics of affected coral species (Johnson and Preece 1992, 1993). The model predicts that there are some disturbance regimes from which the reef system will not recover, but remain in a degraded state of low coral cover indefinitely.

Analysis of the regional patterns of recovery have reinforced the pattern of outbreak movement interpreted from broad-scale survey results. Recovery of hard coral populations on impacted reefs in the Central Section of the GBR lags behind recovery of reefs to the north in terms of both coral cover and colony size (Done et al. 1992). The pattern is reproduced on reef scales where prolonged outbreaks occurred.

Massive corals are significant structural components of coral reef systems. They also play a potentially significant role in understanding the impacts of outbreaks and have been used as evidence to implicate human influences in outbreak causality. Because massive coral species have very slow growth rates (ca. 1 cm/yr) large colonies would take decades to centuries to be replaced after death. While massive corals are not the preferred prey of COTS, they may suffer high mortality in major outbreaks. Because of this slow growth, some researchers have claimed that reefs could not sustain outbreaks at the observed frequency without rapid degradation in, and possibly loss of, massive coral communities (e.g. Cameron et al. 1991). They argue that this is prima facie evidence of increased outbreak frequency (or indeed novelty of outbreaks) in recent times and that this is correlated with particular human activities.

Evidence for the inability of massive coral communities to cope with 15-20 year outbreak return periods was based on surveys of reefs affected by severe outbreaks. In a major study that compared reefs affected by outbreaks to varying degrees and non-impacted reefs, DeVantier (1994) confirmed the significant mortality of massive corals on reefs affected by severe outbreaks (> 200 COTS/ha). However, he found that where outbreaks are less intense (< 100 COTS/ha), there was relatively little effect on assemblages of massive corals.

While some reefs have been affected by outbreaks in both of the two previous episodes, the patchy nature of outbreaks on individual reefs means that the same sites (or coral communities) may not necessarily be affected. This question of patchiness is critical to understanding long-term impacts of COTS outbreaks on massive coral communities. Continuation of current monitoring of benthic communities through the AIMS Long-term Monitoring Program is essential to determine the extent and frequency of COTS outbreak impacts on massive corals in the event of another episode. Such information will contribute significantly to clarifying the historical pattern of outbreaks on the GBR and their sustainability.

Techniques

Monitoring large-scale phenomena, such as COTS outbreak episodes, on the GBR has required development and refinement of cost-effective techniques. During a previous outbreak (1962-1975) the use of a wide range of survey techniques meant that spatial and temporal comparisons were extremely difficult. Standardisation on the manta tow technique has overcome many of these problems, but concern over methodological inconsistencies, as well as the precision and accuracy of the technique needed to be addressed to resolve long-standing contention.

Assessment of manta towing in the field and recording of a range of factors that potentially influenced accuracy and precision provided a number of recommended improvements to the way in which the technique is applied (Fernandes 1991). These recommendations have subsequently been incorporated into the technique. In general, manta towing is regarded as a useful tool for assessing the broad-scale distribution and abundance of qualitative differences between population levels of COTS, and for estimating broad changes in live and dead coral cover. However, there is continuing debate over the ability of the technique to provide accurate and precise estimates of COTS abundances (see Fernandes et al. 1990, De'ath 1992, Fernandes et al. 1992, Moran and De'ath 1992).

The variable nature of outbreaks has provoked considerable debate over what differentiates an outbreak from 'normal' non-outbreaking populations. Moran and De'ath (1992) defined outbreak densities in terms of density (> 1500 km^{-2}) and results of manta tows (>> 0.22 starfish per 2-minute tow). Fernandes (1991) developed a decision-making key and pro forma to formalise the process by which reefs are classified with respect to COTS outbreaks. The key takes into account numbers of starfish detected by the manta tow technique, live and dead coral cover, and historical information. While the technique does not address the issue of differentiating outbreaks from 'normal' populations per se, using the key provides a consistent and standardised way of discriminating between outbreaking and non-outbreaking populations of COTS.

Impact on Fish

Although the effects of COTS outbreaks on coral communities are well documented, there is surprisingly little information on repercussions of such dramatic changes to the benthos for other reef fauna and flora. Intuitively, the influence of substantial coral mortality should flow through affected reef systems to produce marked downstream changes in community structures and trophodynamic relationships. Research to date has focused on numerical responses in fish communities and yielded conflicting results. The size of area studied appears to explain some of the inconsistency between research results. Changes in fish communities tend to be significant on small scales such as bommies (e.g. Sano et al. 1987) but not at reef scales, with the exception of butterflyfishes, many of which are obligate corallivores (e.g. Williams 1986, Ayling and Ayling 1989).

Research conducted through the COTSREC Program by Dr David Klumpp and Mr Tony Hart found no evidence of a post-outbreak response from herbivorous fish at reef scales. Although there was a significantly higher standing crop of turf algae on reefs affected by outbreaks than on non-impacted reefs, there were no detectable differences between the populations of a herbivorous fish species (*Acanthurus nigrofuscus*) on impacted and non-impacted reefs in the central GBR region. Attributes measured included diets, feeding rates, densities, biomass, growth rates and body condition. The results of this study indicate that food supply is not a major limiting factor for coral reef herbivorous fishes.

Larval and Adult Starfish Biology

Aspects of the reproductive biology of COTS have profound implications for the numbers of starfish and the potential for radical population changes. A number of hypotheses on the causes of outbreaks relate to the high potential of *Acanthaster planci* to produce massive numbers of offspring if the conditions for survival and growth are favourable.

Fertilisation success is a fundamental requirement for any animal to maintain their populations. A study of the reproductive biology of COTS by Babcock and Mundy (1993) involved extensive field experiments on Davies Reef in the central GBR. While COTS were observed spawning in the field between December and January, the gonad index peaked early in the spawning season. Measurements of fertilisation rates under controlled laboratory conditions also suggested that the fertility of COTS was high early in the spawning season and then declined gradually. One question that remains unanswered is the extrapolation of these results to other latitudes, particularly to the Cairns Section, where primary COTS outbreaks appear to occur. As shown by Black (1992), the temperature regime in this Section is considerably different from that in the central GBR.

Fertilisation success depends not only on the synchrony in spawning times, but also on the spatial distribution of COTS within reef habitats. Babcock and Mundy (1993) reported that a large number of COTS (129 individuals counted) appeared in a relatively small area and most (68%) spawned in only a few hours. They also observed a diverse range of other invertebrates spawning at the same time. Although little is known about cues that trigger the mass spawning of COTS (and other reef animals), Babcock and Mundy's results indicate that COTS outbreaks may be initiated from a relatively small population of COTS through spawning synchrony and aggregation. Fertilisation rates for COTS in the field were the highest measured for any invertebrate (60-70% fertilisation when males and females were separated by 10 m). Even when starfish were separated by distances of over 30 m about half of the eggs were fertilised. Benzie et al. (1994) confirmed the results of Babcock and Mundy (1993) using calculations based on gamete concentrations found in the field and the fertilisation rates seen in the laboratory at those concentrations. The superior fertilising ability was explained by Benzie and Dixon (1994) who found that the gametes of *A. planci* aged more slowly and sperm maintained a higher fertilising capacity when diluted compared to sea urchins.

Birkeland (1982) proposed that primary COTS outbreaks were caused by heavy terrestrial runoff increasing nutrient inputs into reef waters. Higher levels of nutrients subsequently increase larval COTS food supplies (phytoplankton). This in turn results in mass settlement of larvae. The underlying premise is that COTS larval growth and survival are food limited under 'normal' conditions. Surprisingly, the debate over Birkeland's hypothesis (the terrestrial runoff hypothesis) has been developed without sufficient knowledge on the food sources for COTS larvae. A series of laboratory experiments were conducted to investigate the likelihood of COTS larvae deriving their nutrition from bacteria and dissolved organic matter (Ayukai and Hoegh-Guldberg 1992). The results indicated that COTS did not ingest bacteria, and that although they ingested photosynthetic picoplankton (< 2 μm) and took up both dissolved free amino acids and mono-sugars, these were unlikely to make a significant contribution to the nutrition of larvae.

The importance of photosynthetic nanoplankton (> 2 μm) as a food source for COTS larvae has been confirmed by the work of Ken Okaji. He demonstrated that both the growth and development rates of COTS larvae in experimental conditions are limited by food availability. Seawater enriched with additional nutrients resulted in faster growth and shorter times to settlement compared to natural seawater. This result lends further support to Birkeland's hypothesis and suggests that human activities that contribute to nutrient enrichment of GBR waters may increase larval COTS survival. Further monitoring of the concentrations of phytoplankton and non-phytoplankton food sources is needed to establish the relative importance of these in the field and to clarify the role food limitation may play in controlling starfish numbers.

Very little research into the early post-settlement stages of COTS has been possible because of the difficulty in finding small COTS juveniles in the field. There are, however, a few exceptional places, where a large number of COTS juveniles have been found. A study in one of these places, Suva Reef in Fiji, reported that the growth of COTS juveniles was relatively slow during an algal feeding period (2.6 mm/month between 7-13 months), but this accelerated following a switch in diet from algae to coral (16.7 mm/month between 13-16 months) (Zann et al. 1990). Sexual maturity was reached in two years. The longevity of one cohort of COTS was estimated as seven to eight years, whereas another cohort collapsed in two to three years, because of disease associated with an undescribed sporozoan. Based on these results and the record of COTS outbreaks, the inter-annual variation in COTS recruitment over fifteen years was inferred and compared with the rainfall record during their spawning season. This revealed no correlation between COTS recruitment and rainfall. As mentioned by Zann, however, this is not considered as a disproof of the terrestrial runoff hypothesis, as his observations were made for secondary and/or chronic outbreak populations. He has also suggested the possibility that the normally high rainfall and regular mid-summer cyclones in Fiji regularly create favourable conditions for COTS larvae.

On the GBR, the inter-annual variation in COTS recruitment was studied by determining the size-frequency distribution of outbreak populations and defining year classes based on its modes (Kenchington 1977). This method, however, is not always reliable, as the size (body diameter) of COTS is highly susceptible to the quantity and quality of diet and even decreases under poor food conditions. An alternative method for age determination is to measure growth bands in skeletal elements (for COTS, in aboral spine ossicles) which appear to grow constantly, regardless of food conditions and somatic growth (Stump and Lucas 1990). The study involved detailed examinations of the basal growth of the spine ossicle and the nature of the growth bands using the tetracycline staining technique. Although the method developed has successfully resolved the age structure of adult COTS populations in the field, size frequency and growth data is still required to estimate the age of juvenile starfish as the bands appear only in starfish aged 2+ years.

The inability to sample the same cohort of COTS juveniles over an extended period and determine the survival/mortality and its controlling factors is a major reason why the COTS phenomenon is so poorly understood (Moran 1986). Although Zann's study is unique in this regard, coral reefs and the surrounding environment of his study sites (Fiji) are different to the GBR, making it difficult to extrapolate to local conditions. One approach to solve this problem is to raise COTS juveniles under laboratory conditions and use them for different types of field experiments (e.g. Keesing and Halford 1992). Although this approach has been successful, the method for mass rearing of COTS juveniles itself is still incomplete and does not guarantee reproducible yields. Reasons for this inconsistency are unknown at this stage, although there are a number of possibilities, including senility of starfish, a narrow optimal spawning window, and inter-annual variability in reproductive success (as noted by several researchers for a variety of coral reef organisms).

Geological Perspectives

This area of research epitomises the controversy surrounding every aspect of the COTS issue. A number of projects funded through the COTSARC Program investigated outbreaks from geological perspectives in an attempt to assess the novelty of recent outbreaks or the exacerbation of outbreaks since European settlement. Sorting and analysis of surface and sub-surface sediments to recover COTS skeletal elements led researchers in this area to conclude:

- individual outbreaks cannot be identified because of the imprecision of dating techniques and the disturbance of stratigraphy as a result of bioturbation;
- despite these limitations, the density and distribution of skeletal elements in the sediments suggest that large populations of *Acanthaster planci* are not a recent phenomenon, but have occurred for the past 3000 to 7000 years on the GBR; and
- there was no evidence to suggest that recent outbreaks differ to those in the geological past, in terms of spatial extent or intensity.

While the geologists were confident of these conclusions, a number of biologists disagreed with the interpretation of results as demonstrating the antiquity of outbreaks on the GBR. Criticism was founded on a number of vital assumptions, viz. (i) that the majority of starfish from outbreak populations remain and die on the host reef, (ii) that reefs which have had recent COTS outbreaks can be discriminated from those which have not by the abundance of skeletal elements in sediments, (iii) that outbreaks will significantly increase the number of skeletal elements above normal background levels; and (iv) that the age of individual skeletal elements can be predicted from the age of their surrounding sediment or their depth in the sediment pile (Keesing et al. 1992). A special edition of Coral Reefs (Volume 11 (2)) presents the criticism and responses in detail.

In an attempt to resolve the conflict of opinions, the GBRMPA convened a workshop 'A Geological Perspective on the *Acanthaster* Phenomenon' in May 1990. No consensus on the conclusions of the geological research was reached, although a number of gaps in current knowledge which confused interpretation of the findings were identified. The Geological Working Group was subsequently established by COTSREC to identify further research that would address these gaps (and any others identified). Dr Don Kinsey (then Executive Officer of GBRMPA) was appointed as chair of the group.

The Working Group recommended a number of pilot investigations including alternative dating techniques, location of sites with minimal bioturbation and sites where accumulation of skeletal elements might occur, as well as behavioural studies to determine where COTS go/die at the end of outbreaks. To date, none of these pilot studies has produced any substantial leads. The status of this area and options for future directions were assessed by the new Chair of the Working Group, Professor David Hopley of James Cook University. Hopley concluded that a sedimentological approach to the question of outbreak antiquity could not progress until the above four questions posed by Keesing et al. (1992) were answered. He suggested an alternative approach of investigating records that may exist in massive corals. This is being pursued in the 1995-96 program.

Controls

The GBRMPA has a long standing policy of permitting local-scale controls of COTS in areas important to tourism or science. This policy reflects both cost-benefit considerations of control efforts as well as uncertainty as to the naturalness of the COTS phenomenon. The Authority's philosophy on this issue is that in the absence of sufficient evidence to suggest human causation or exacerbation of COTS outbreaks there is no justification for attempting large-scale controls of what could be an entirely natural cycle (see Appendices 5 and 6). Independent reviews of this policy have supported the Authority's policy.

Local-scale controls using injection of toxic substances have been shown to be relatively effective in protecting small areas of reef. The preferred compound for these controls has been saturated copper sulphate ($CuSO_4$). However, there have been concerns of environmental contamination resulting from excessive use of the toxin in relatively small areas of reef.

GBRMPA controls research focussed on (a) establishing the minimum dose level of copper sulphate required to kill mature starfish and (b) identifying suitable environmentally friendly alternatives. Minimum copper sulphate dose levels were established (4-8 ml of saturated solution for adult starfish) and a viable alternative to copper sulphate was found. Sodium bisulphate (commonly sold as *Dry Acid* - a swimming pool chemical to lower pH) was effective in killing COTS and it is environmentally benign, leaving no toxic trace elements. The technique is described in a published manual (*Controlling Crown-of-thorns Starfish*) and it is currently being used by a number of tourism operations to effectively control starfish in limited areas.

In most cases, local-scale controls of COTS require a permit from the GBRMPA and QDEH (see appendix 5). Permits require permit-holders to report periodically to the Authority on the following:

- starfish numbers/density at the start of the control program;
- the extent and depth of the area affected;
- methods used for surveys and controlling starfish numbers;
- numbers and sizes of starfish killed or removed;
- dive hours spent on the control program; and
- costs.

This information facilitates assessment of the status of reef areas and the success of control operations. Currently, three tourism operators visiting reefs off Cairns have been issued with such permits. Processes to streamline the issuing of permits have been implemented.

Hydrodynamics, Recruitment and Terrestrial Inputs

Because of the extreme logistical difficulties associated with trying to monitor the dispersal of COTS larvae in water currents, computer modelling has been used to simulate the movement of larvae between reefs. Much of the computer modelling in the past seven years has centred around the development of numerical hydrodynamic models for resolving the dispersal pattern of COTS larvae on large (e.g. Dight et al. 1990) and small spatial scales (Black and Gay 1990). These models seem based on robust modelling techniques, and general patterns predicted by the models match fairly well with the observed pattern of outbreaks on the GBR. However, the models require a number of critical assumptions as well as simplification of reef structure and processes. Until assumptions are validated against reliable field data Johannes and the COTSREC have recommended that models be used only for limited and prescribed purposes. An urgent need was felt for set standards for the development and use of hydrodynamic models for management decision making. This need is currently being addressed by the Authority through a consultancy to Dr Frank Wilkinson.

Modelling studies have identified hydrodynamic processes which play a prominent role in the dispersal of larvae. These include (1) low frequency, barotropic flows associated with the East Australian Current (EAC), (2) still essentially low frequency, wind forced flows, and (3) relatively high frequency tidal flows. The hydrodynamic model SURGE was modified by the Marine Modelling Unit at James Cook University and used for examining the scale and relative importance of these processes for the Cairns Section, where the past two major COTS outbreaks were first recorded (Dight et al. 1990). This model predicts that (1) EAC-associated flows are relatively weak in the north, but intensify farther to the south away from the EAC bifurcation, (2) the dense reef matrix significantly reduces the development of wind forced flows, (3) the amplitude of tides is relatively large in the south, and (4) flows within the reef matrix follow natural passages, resulting in a degree of phase retardation in tidal flows. The model seems successful in demonstrating that the hydrodynamic regime in the north behind the ribbon reefs is markedly different from that in the South.

A current 'best-use' model for simulating the large scale dispersal of COTS larvae is based on three transport component outputs from SURGE (East Australia Current, winds and tides) and runs under time-dependent tidal flows and a randomly varying wind field that is typical during the spawning season of COTS (Dight et al. 1990). This model is capable of generating outputs that are qualitatively consistent with observations made for the past two major COTS outbreaks: e.g. the southward movement of COTS outbreaks to the south of Cairns and the high incidence of COTS outbreaks in mid-shelf reefs (James and Scandol 1992). However, the consistency between the results of dispersal simulations and observed outbreaks at the level of individual reefs is less convincing. Resolution at this scale is vital to the identification and validation of individual source and sink reefs. There are a number of reasons why this level of detail is unachievable at this stage. The model runs under 'average' conditions; and does not take into account the role of fine-scale hydrodynamic processes on the movement of COTS larvae in close proximity to reefs and their possible retention on reefs. There are also a number of shortcomings associated with records of outbreaks on the GBR (for comparison with simulations) with incomplete data on affected reefs and the uncertainty over when outbreaks started on particular reefs.

The model developed for fine-scale resolution of dispersal around reefs predicts much longer residence times of COTS larvae than previously thought and suggests the potential importance of self-seeding as a mechanism for COTS outbreaks (Black et al. 1990). This model is highly sophisticated, but still suffers from a degree of uncertainty due to assumptions that have not been validated against field data. Attempts to gain funding to field test this model have been unsuccessful. Research by Benzie et al. (1994) also highlights the importance of hydrodynamic regimes to self-recruitment.

A hindcasting model for low frequency currents along the GBR successfully explained how the southward movement of COTS outbreaks occurred in a wave of secondary outbreaks. It also provided an interesting view that the initiation of the last major outbreak coincided with the period of slow currents. This model was calibrated against current meter data and proven to be statistically efficient. The model, however, is essentially applicable only to the central GBR and its relevance to the Cairns Section may be questionable. As mentioned earlier, the physics of the Cairns Section is different from that in other parts of the GBR. There is a possibility that the dispersal of COTS larvae in the Cairns Section is under a strong influence of high frequency tidal flows rather than the East Australian Current, low frequency flows or wind forced flows.

The number of COTS larvae settling on individual reefs is affected by a number of physical and biological factors. Temperature is one of these factors (Lucas 1973). The data on the sea surface temperature along the GBR during the spawning season of COTS over the past thirty years was statistically analysed and viewed in relation to the reported range of temperature for larval survival (Black 1992). Interestingly, the optimum temperature of 28°C for larval survival occurred at 16°S, which had been identified as the initial epicentre of COTS outbreaks. This coincidence, however, needs to be interpreted carefully. Firstly, the analysis does not take the horizontal and vertical variations in temperature into consideration. Secondly, Lucas' results indicate that the optimum temperature is around 28°C, but not exactly at 28°C. Lucas also found a strong interaction of temperature with salinity. It is, therefore, more appropriate to say that the temperature in most parts of the Cairns Section during the spawning season of COTS is generally suitable for larval survival.

It has often been assumed that COTS recruitment in the GBR occurs in isolation from terrestrial influences, as their habitat is away from the mainland. The study of environmental records in the skeleton of long-living massive corals on Green Island, however, suggests that this is not always the case (Rasmussen et al. 1992). The highlight of this study is a positive correlation between agricultural fertiliser usage on the nearby mainland and skeletal magnesium concentration, which has been suggested to increase with increasing concentration of organic matter in seawater. However, a possibility that the observed change in skeletal magnesium concentration is due to a natural change in ocean productivity is not precluded. The skeleton of massive corals on a shelf-break reef records a significant change in global environment between the 1940s and 1970s, which appears to coincide with the period when agricultural fertiliser usage increased dramatically.

Most controversial debates on COTS recruitment stem primarily from the fact that both larval and juvenile COTS are rarely seen in the field. Because COTS larvae closely resemble larvae of other starfish alternative identification techniques have been developed. Monoclonal antibodies that are specific to COTS larvae have been cultured. A field-based assay system is yet to be developed. Attempts to collect larvae in situ settlement tubes have been unsuccessful (perhaps because of the timing and placement, but also because of the large amounts of foreign material collected).

An attempt was made to locate high density populations of juvenile COTS during the last major outbreak using small feeding scars as a guide of their activity. This attempt was unsuccessful, as a large proportion of small feeding scars were attributed to coral feeders other than juvenile COTS, particularly of *Drupella*.

Predation

While the view that over-collection or over-fishing of COTS predators has caused or exacerbated outbreaks has been strongly advocated by some proponents, support from research remains scant. Research has approached the testing of this hypothesis from a variety of angles:

- feeding trials and gut content analysis to establish predators of COTS;
- surveys of marine experts for anecdotal information on the identity of COTS predators and the incidence of predation;
- analysis of fish catch records to assess possible effects of fishing on putative COTS predators;
- comparisons of putative predator densities on reefs that have been affected by outbreaks with densities on reefs that haven't;
- modelling the effects of predation on COTS populations; and
- experimental manipulations to measure predation rates of juveniles in the field.

Identification of COTS predators is fundamental to many of these approaches. Although feeding trials demonstrated that a variety of fish species ate large juvenile and adult COTS under artificial conditions, extrapolation of the results to natural conditions is debatable. Preliminary experiments where laboratory-reared small juvenile COTS were presented to fish predators in the field indicated that lethrinids will eat juvenile starfish but they are not a preferred food (Sweatman 1995a, b). Analysis of the gut contents of ninety-five *Lethrinus miniatus* (an inferred major fish predator of *A. planci*) collected from a reef with high COTS densities found no evidence of predation on adult COTS.

Observations of predation on COTS in the field by marine scientists and other experts identified a number of predators, some of which are, or have been, targeted by commercial and recreational fishers. The giant triton, *Charonia tritonis*, was the most commonly observed predator (accounting for nearly half of all observations). However, this high proportion of observed predation events may be attributed to the long duration of such events compared with other predators. Collection of *C. tritonis* on the GBR has been banned since 1969. Fish predators included maori wrasse (*Cheilinus undulatus*) and several species of lethrinids. The rarity of observed predation events highlighted the impracticality of using direct observation as a means to measuring predation in the field.

Analysis of Queensland Fish Board landings, records from sample charter operations and recreational spearfishing competitions to address the question of fishing pressure on putative COTS predators proved fruitless because of inadequate and confused record keeping (Steven 1988). Reporting systems changed over the twenty-five year period, taxonomy and common names of fish were inconsistent and no statistics were included to allow any assessment of fishing effort. The lack of confirmed predator identities further limited the value of this study in understanding the effects of fishing on COTS predators.

Because of a lack of detailed COTS life history information (such as larval survivorship and settlement rates) and a lack of knowledge of critical predation parameters (such as feeding rates and feeding behaviour), modelling cannot establish a minimum predation level that would prevent outbreaks (McCallum 1994). However, models predict that any predator capable of increasing starfish mortality by one percent per day would be important and that predator densities of ten per hectare are sufficient to have a substantial impact on starfish numbers. Models also indicate that the searching behaviour of predators is critical for the prevention of primary outbreaks, while the maximum rate of prey consumption is more important in preventing secondary outbreaks. The sorts of predators that have significant impacts in these two situations are therefore likely to be different. The observations of Mr Lyle Squire (reported in Marine Bio Logic 1991) are interesting in this regard. He noted several occurrences of COTS in the stomachs of maori wrasse (*Cheilinus undulatus*) fished from northern GBR reefs where COTS were rare. The suggestion is that this species (which is targeted by commercial and recreational fishers) was actively searching for COTS when the starfish was rare.

Other models have also been hampered by a lack of critical information on predators and COTS life history information, but they have provided some useful insights into possible mechanisms of outbreak causality and highlighted critical areas for further research. The model of Ormond et al. (1990) concluded that predator densities of 5-20 per 2000 m^2 of reef front would be sufficient to prevent outbreaks, providing larval recruitment was not exceptionally high. Such predator densities were found on Red Sea reefs and on sampled GBR reefs that had not been affected by outbreaks. Lower predator densities occurred on sampled GBR reefs that had experienced outbreaks.

The estimated predator density to regulate COTS populations predicted by Ormond et al. (1990) is two to ten times higher than that estimated by McCallum (1994) to have a substantial impact on COTS populations. This disparity highlights the need for additional information on key parameters to more realistically scope model assumptions.

Juvenile starfish are likely to be more vulnerable to predation because of their small size and because their spines are less well developed than those of adults. Because large numbers of juvenile COTS have not been located in the field in recent years it has been necessary to rear starfish for experimental work. Two projects have used these starfish to look at aspects of predation.

Placement of reared juvenile starfish in the field under a variety of experimental conditions has demonstrated that recently-settled starfish experience very high mortality rates due to predation, probably by crustacean meiofauna (Keesing 1993). Predation rates are size-dependent, reducing from around eight percent per day for newly settled starfish (< 1 mm diameter) to around one percent per day for 6-month old starfish (approximately 13 mm diameter). Based on these figures, Keesing (1993) concluded that mortality during the first year of life is likely to account for the most important influence on eventual COTS population size.

Predation rates on larger juveniles (15-79 cm diameter) were lower (0.34% individuals per day) and insignificant in a single trial of caged and uncaged starfish conducted by Sweatman (1995a, b). This rate of predation is lower than that predicted by models (McCallum 1994) to be required if population regulation by predators is to be achieved. However, the average mortality rate from predation in the first year may come close to McCallum's critical predation rate. Experimental manipulations of juveniles in the field need to be repeated at additional locations (on reefs subject to differing fishing pressures), however failure in the rearing program has forced deferral of any further work in this area.

Public Information

The COTS phenomenon on the Great Barrier Reef has long been an issue of great media and public interest. The often sensationalised reporting by both the printed and electronic media has made outbreaks of COTS one of the most emotive coral reef management issues. Recent increases in the numbers of COTS on some reefs off Cairns and around Lizard Island have again highlighted the need for a proactive public information strategy aimed at providing a balanced view of the issue.

At their November 1993 meeting, COTSREC recommended that a comprehensive public education strategy dealing with the COTS phenomenon be implemented. A detailed document outlining the main components of a targeted strategy was accepted by the Committee in early 1994.

In addition to actively promoting the achievements of the COTSREC Program, the Committee sees its public information strategy as playing an important role in maintaining a sensible, non-emotive discussion of the issue in the public forum.

The main objectives of the public information strategy are:

1. To provide up-to-date, relevant information on research progress and other developments in relation to the crown-of-thorns phenomenon to members of the general public, the media and Reef-user groups.
2. To get Reef-users actively involved in the COTSWATCH survey scheme.
3. To identify and address the particular educational needs of teachers and students at all levels of the education system dealing with marine environmental issues.

The strategy has four main components - the implementation of the COTSWATCH Reef-user survey scheme, design and distribution of educational materials, promotion of displays in aquaria and zoos as well as a media component.

The COTSWATCH Reef-user survey scheme

Public participation schemes in relation to the COTS issue have been running since the early 1980s when they were first recognised as a cost effective way of getting qualitative information on the reef-wide distribution and abundance of COTS. In the early days of these schemes, both time and budgetary constraints affected their effective promotion with the degree of public participation suffering accordingly. However, COTSREC recognised that an adequately funded and coordinated scheme would be highly beneficial to the COTS Program and the Authority at large. In addition to playing an important role in public relations, a Reef-user survey scheme has the potential to fill in existing information gaps. The AIMS broad-scale surveys have some inherent limitations that can, in part, be overcome by this scheme. A new improved survey scheme named COTSWATCH was launched in late 1993. Personal communications with scientists, Reef-user groups and members of the general public had previously identified some of the shortcomings of past schemes. A number of significant changes were made to address the concerns highlighted by contributors.

The main characteristics of COTSWATCH:

- A reward system ensures that contributors to the COTSWATCH scheme get regular feedback on their observations. Informative brochures and newsletters are distributed free to all contributors. Regular input into the scheme is particularly desirable and is being encouraged at every opportunity.

- The information received from Reef-users is entered into a dedicated database allowing for analysis and fast retrieval of survey results. The database is linked to a simple geographical information system (IRIS) allowing survey results to be viewed in a regional context.

- *Reef Research*, the quarterly newsletter of the Research & Monitoring Section of GBRMPA is the principal means of disseminating information obtained through the scheme. Contributors to the COTSWATCH scheme get an up-to-date summary of the latest findings and are acknowledged in the regular column on COTS.

- Regular public lectures (six monthly updates) on the progress and status of the Program are presented in the main regional centres along the Queensland coast between Cooktown and Gladstone. These presentations mainly target QDEH staff, local tourism operations, members of environmental volunteer schemes and Marine Park Advisory Committees.

The COTSWATCH scheme was instrumental in detecting the recent increases in the number of COTS on some reefs in the Cairns Section of the GBR Marine Park (Lassig and Engelhardt 1994).

Educational Materials

The Authority has released two popular-style products aimed at informing the general public of the results and progress of the COTSREC Program.

A booklet, entitled '*Crown-of-thorns starfish - Research Update 1991/92*' was published in January 1993. In addition, a documentary-style video ('*The Crown-of-Thorns Phenomenon*') was produced in collaboration with the Australian Institute of Marine Science. Both of these releases replaced earlier products produced in the late 1980s. The semi-scientific Research Update, in particular, has been very successful in informing a wide cross section of the public. Some 1800 copies of the booklet have already been distributed.

In an effort to further improve the user friendliness of these educational materials, the COTS public information strategy is seeking input from experts in the fields of primary and secondary education. As part of the initial phase of this process, science subject masters and school librarians have been asked to assist in identifying the particular needs and requirements that should be considered in the future.

Printed and Electronic Media

Throughout the history of the COTSREC Program, both the printed and electronic media have played an important role in informing the public of the status of COTS on the Great Barrier Reef. However, there is no consistent standard of reporting within the media. Sensationalised reporting still dominates, particularly in the printed media.

Recent increases in COTS numbers on some northern reefs have again resulted in extensive media coverage throughout Queensland and Australia. In our dealings with the media, the newsletter *Reef Research* has been shown to be an effective means of providing a more balanced view of the issue. Many local and regional newspapers and television networks now refer to the newsletter as a main source of information.

A more detailed media strategy aimed at further improving the quality of reporting has been prepared following consultation with key stakeholder groups (tourism industry representatives, managers and researchers). The strategy identifies clients of the COTS Program who are best communicated with through the media, describes the concerns and needs of these clients, defines the objectives of communication with the clients and outlines key messages to address these objectives

Displays at Aquaria and Zoos

An exhibit on the COTS phenomenon has been established at the Authority's prime educational facility, the Great Barrier Reef Aquarium in Townsville. This exhibit includes an aquarium display of living COTS as well as an interactive computer program that explains various research and management aspects of the issue. This recently updated program is proving popular with the general public.

Displays at aquaria and zoos are potentially very useful in communicating aspects of the COTS phenomenon to large audiences. However, the current trend of moving toward the use of interactive rather than static displays often requires the availability of considerable funds. Although funding support may be limited, the COTSREC strongly encourages development of educational displays on the crown-of-thorns starfish in both zoos and aquaria.

The Possible Causes of Outbreaks

Understanding the causes of COTS outbreaks on the GBR is critical to the efficient and effective management of the GBR Marine Park. The Authority's policy is not to interfere with COTS populations on a large scale unless it can be shown that outbreaks are caused or exacerbated by human activity (appendix 5). The policy treats *Acanthaster planci* as a natural inhabitant of the Reef and is based on sound risk-benefit principles (see appendix 6).

Results of the COTSREC Program to date suggest the following about the causes of COTS outbreaks:

- it is likely that there are multiple causes of outbreaks;
- on the GBR, outbreaks are initiated through a number of consecutive successful recruitment events over a fairly wide geographic area;
- both natural events and human activities may be involved in outbreaks; and
- of the two most frequently hypothesised causes of outbreaks (reduced predation on COTS through over-fishing of natural predators; increased survival of COTS larvae through changes in water quality), the latter is most strongly supported by research results to date.

These conclusions are based on the authors' assessment of the available information, but they are also shared by the majority of scientists and managers who have been involved in the COTS issue. A total of seventy-four scientists and managers (from 101 mailed questionnaires) responded to a survey seeking their opinions on a series of aspects related to COTS research. Most of these experts (64%) indicated that evidence for human activities causing or exacerbating outbreaks does not exist, although a substantial proportion (27%) were undecided. A clear majority (88%) of respondents indicated they thought it likely there were multiple causes of outbreaks rather than a single cause (see figure 3).

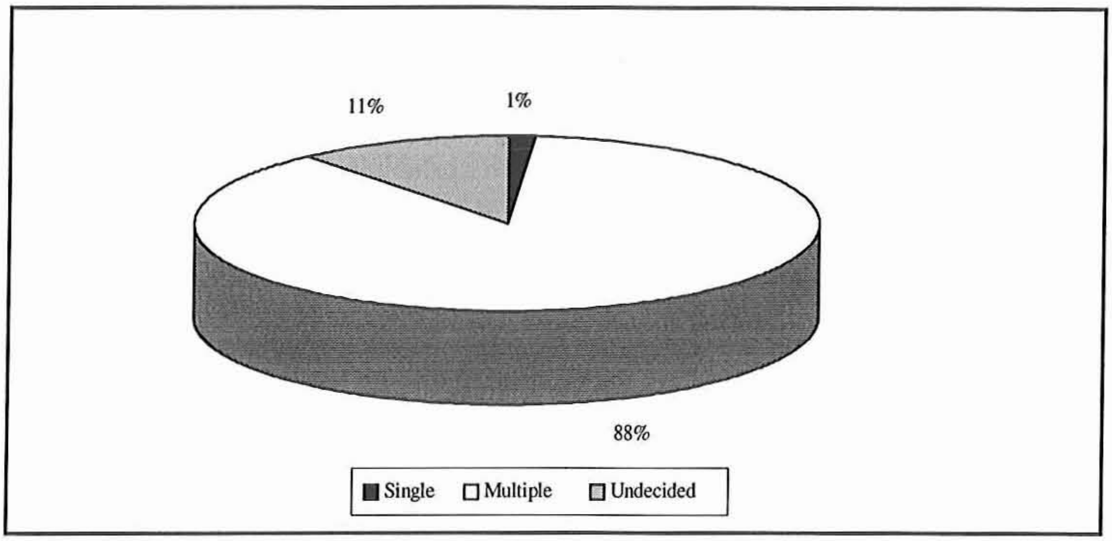

Figure 3: Responses of scientists and managers to the survey question *'Do you think that there is likely to be a single cause of COTS outbreaks or a number of factors contributing to primary outbreaks?'*

Another survey question asked respondents what they thought were the most likely causes of primary COTS outbreaks. Options given were natural (increased larval survival/recruitment from favourable water quality conditions; larval retention on natal reefs; other) and human influences (removal of predators through over-fishing or collecting; increased nutrients/reduced water quality; other).

Of the two primary choices between natural causes and human influences 12.5% of respondents indicated natural causes only, 3.3% indicated human influences only and 84.2% stated that a combination of natural and human influences was likely to be responsible for outbreaks. In both natural and human influence contexts, water quality factors were regarded as the most likely receiving 57.3% and 60.3% of the responses in each of those categories respectively (figure 4).

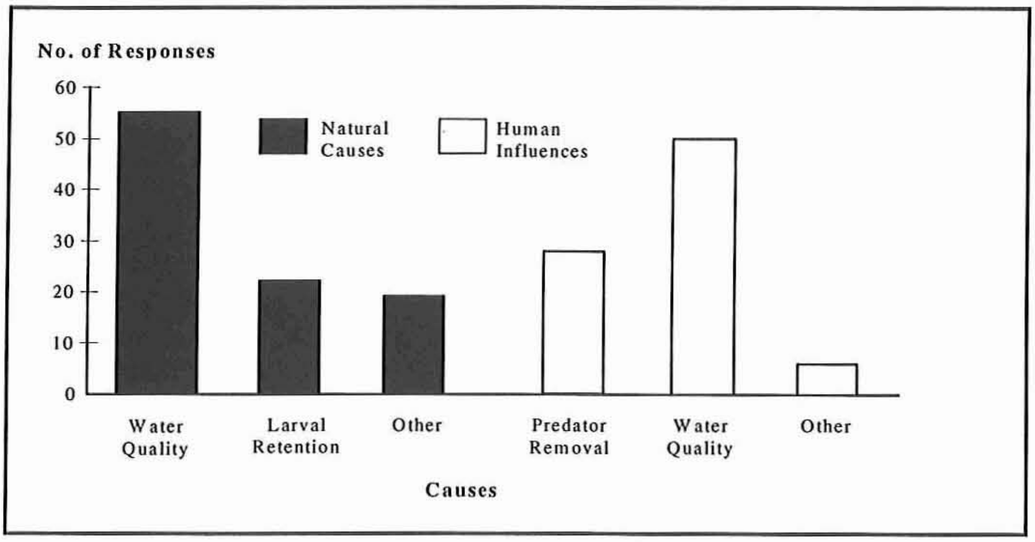

Figure 4. Responses of scientists and managers to the survey question *'Based on existing evidence what do you think are the most likely causes of primary COTS outbreaks?"*

FUTURE PROGRAM DIRECTIONS

The COTSREC and the Authority have used three mechanisms to review COTS research and to recommend on future research directions:

- workshops;
- ad hoc working groups; and
- reviews by individuals with expertise in particular areas.

There have been three major COTSREC workshops (A Geological Perspective on the *Acanthaster* Phenomenon in May 1990; Reproduction, Recruitment and Hydrodynamics in the Crown-of-thorns Phenomenon held in May 1991; The Possible Causes and Consequences of Outbreaks of the Crown-of-thorns Starfish held in June 1992) and four working groups (Geological Working Group; COTS and Water Quality Working Group; Predator Working Group; Massive Coral Working Group).

The COTS Program has four primary objectives:

1. to monitor COTS and their effects on the GBR;
2. to establish the causes of COTS outbreaks and, in particular, to establish the role of human activities in causing or exacerbating them;
3. to develop policy in relation to the COTS issue and advise on appropriate management responses; and
4. to inform the public of the results of COTS research and monitoring of the GBR.

This chapter addresses these objectives and presents new and continued initiatives required to meet them. Specific directions will evolve as the status of COTS populations on the GBR change and as more knowledge is acquired. Many of the objectives are long-term by virtue of the complexity of the issue and the apparent cyclicity of outbreaks. Missed opportunities to study initial causes of outbreaks, for example, may result in delays of up to twenty years (based on the interval between the previous two outbreak episodes).

Monitoring COTS and their effects on the Great Barrier Reef

Three main forms of monitoring have been used to provide information on the distribution of COTS on the GBR:

- Reef-user COTS sighting schemes;
- Broad-scale surveys; and
- Fine-scale COTS surveys.

The Reef-user COTS sighting scheme (COTSWATCH) was originally implemented in the early 1980s because low levels of funding precluded the implementation of formal broad-scale scientific surveys. COTSWATCH has been particularly successful (in terms of questionnaire return rates) over the last two to three years, largely because of efforts to regularly promote the scheme and to disseminate information resulting from responses. Information provided by respondents, although qualitative, was responsible for detecting recent increases in COTS numbers on reefs between Cairns and Cooktown. The scheme has also been successful in providing a platform for keeping the public informed of the status of COTS outbreaks and the results of research.

> Future Direction 1: *Because of the success of COTSWATCH in providing detailed site information on COTS abundances and its role in providing a platform for extension activities, the scheme should be continued.*

Annual broad-scale surveys of the GBR have been conducted by AIMS since 1985. Over that time there has been a substantial increase in our understanding of the extent and dynamics of the COTS phenomenon. The surveys have provided information on the origins, patterns and rates of movements of outbreaks as well as the general status of surveyed reefs. Since 1992 the broad-scale surveys have acted as a basis for more detailed monitoring of benthos, fish and water quality at selected sites on around eighty reefs each year.

Results of the broad-scale surveys confirmed the increase in COTS numbers on reefs in the northern GBR detected through the COTSWATCH scheme.

> Future Direction 2: *Because of the long-term value of broad-scale surveys, the 'big picture' information they provide, and the basis for more detailed monitoring they serve, these surveys should be continued.*

At the same time there is a critical need for detailed information on COTS population dynamics prior to large-scale outbreaks. Because monitoring programs were not in place before the previous two outbreak episodes, the dynamics leading to such episodes are unknown. Because of increasing numbers of (particularly juvenile) COTS on reefs in the suspected source area of outbreaks on the GBR, fine-scale surveys based on the belt transect method were implemented in 1994-95. These surveys have provided detailed information on the status of COTS populations on mid-shelf reefs in the area, including starfish densities and population structure. With this information it is possible to hindcast the timing and extent of recruitment events and to make projections on likely changes to COTS populations. At even finer scales, detailed studies of COTS populations on particular reefs can provide necessary information on critical parameters such as recruitment, migration and mortality rates. A combination of these three scales of information is critical to understanding the causes of outbreaks and for the development of appropriate management responses. The combination of broad- and fine-scale surveys, as well as local COTS population dynamics studies, provides detailed information for key areas while maintaining the necessary wider perspectives.

> Future Direction 3: *The fine-scale surveys of COTS on selected mid-shelf reefs between Cairns and Cooktown and detailed studies of COTS population dynamics on particular reefs should be continued to record the status of reefs in the area and to monitor changes in COTS populations over time.*

The effects of major COTS outbreaks on massive coral communities have been used to support the argument that outbreaks in recent times are novel events or, alternatively, evidence of increased outbreak frequency. A concurrence with increased human activity has led some scientists to conclude that human activities are therefore responsible for outbreaks. Measurements of the effects of outbreaks of different intensities on massive coral communities have recently provided evidence that conflicts with this extrapolation. Further information on the dynamics of massive coral communities before and during outbreaks (on a large number of reefs) is needed to resolve the frequency with which particular communities are affected.

> Future Direction 4: *Further monitoring of massive coral communities on a reasonably large number of reefs to provide information on population dynamics before and during outbreaks is needed.*

The Origins and Causes of Outbreaks

Both of the two previous outbreaks and the recent increase in COTS populations originated in the Cairns Section of the GBR Marine Park. While other independent outbreaks have occurred outside of this area on the GBR, this consistency raises the question of whether or not the Cairns Section has some characteristics that pre-dispose it to primary outbreaks. Although some models suggest that the northern origin and southward progression of outbreaks is imposed by coral cover (i.e. food) limitations following the first outbreak, the patchiness of coral mortality and variability in outbreaks weakens this argument.

> Future Direction 5: *A desktop study to investigate the possible 'uniqueness' of the Cairns Section of the GBR Marine Park should be conducted to provide insights into why COTS outbreaks are initiated in this area. The study should include the following components:*
> - *hydrodynamic characteristics;*
> - *geomorphology;*
> - *recent history of episodic events that have affected the area (e.g. cyclones and floods);*
> - *nutrient sources;*
> - *nutrient distribution in space and time;*
> - *phytoplankton community composition;*
> - *anecdotal information; and*
> - *commonalities with other areas that have experienced periodic outbreaks.*

While it is known that two previous outbreaks and the recent increases in COTS populations originated in the Cairns Section, the dynamics leading up to these situations is unknown. Large-scale hydrodynamic models point to an outbreak epicentre behind the Ribbon Reefs at around 16°S, but there is no information on the scale of the epicentre (single reef, reef cluster or larger area). Modelling by Dr Kerry Black of VIMS and the results of the fine-scale surveys suggest that the origin may cover up to two degrees of latitude. Knowledge of the scale is critical in understanding outbreak causality and the spread of outbreaks as well as in developing appropriate management responses.

> Future Direction 6: *Genetic studies to determine the degree of connectivity among currently increasing COTS populations in the Cairns Section should be conducted, together with field measurement of hydrodynamic conditions.*

It is likely that outbreaks are caused by a variety of factors, and it is possible that these differ in both space and time. On the GBR many factors contributing to outbreaks may be operating concurrently. The situation is further complicated by the relatively high degree of connectedness between reefs making it difficult to differentiate primary and secondary outbreaks. Knowledge of the status of COTS populations in other areas, together with information on key environmental parameters, could provide useful insights into the causes of outbreaks and the degree of connectivity between geographically spread reef systems.

> Future Direction 7: *An international COTS information network should be established to gather and collate details of the status of COTS populations throughout the Indo-Pacific region.*

Acanthaster planci is a very specialised animal, but it shares many of its biological and ecological characteristics with other reef species. For example, many reef species produce planktonic larvae that feed on phytoplankton and settle after similar lengths of time in the plankton to *A. planci*. There are many species (including other species of starfish) that feed on coral. These similarities with other species raises the question of whether or not other species undergo similar substantial population fluctuations to COTS. It may be that other species do 'outbreak', but because the species have a lower profile than COTS they go unreported, or their significance is not realised. If 'outbreaks' of other species have occurred and coincided with those of *A. planci*, the shared biological/ecological characteristics could shed light on causative factors.

Future Direction 8: *A desktop study to review existing data on recruitment of other coral reef organisms over the past thirty years to determine whether or not 'outbreaks' have occurred.*

From a management perspective it is imperative to determine whether or not there is a connection between human activities and COTS outbreaks. If such a connection exists, managers have a responsibility to attempt to regulate that activity or at least ameliorate its effects.

There is general agreement among scientists and managers that two primary mechanisms for human activities causing or exacerbating COTS outbreaks exist:

- increased survival of COTS larvae through elevated nutrient levels caused by coastal and catchment modification resulting in higher food availability for larvae; and
- over-fishing or over-collecting of predators.

Water Quality

Water quality has been implicated as both a natural and human-influenced cause of COTS outbreaks. In a recent survey of researchers and managers familiar with COTS research, most regarded factors associated with water quality as being the most likely causes of outbreaks.

Gaps in our knowledge identified by working groups, workshops and individual reviews provide the following questions that need to be addressed by research into connections between COTS outbreaks and water quality:

- Has human activity (coastal development, catchment modification etc.) increased nutrient inputs into GBR waters over the last fifty years?

Research to date (e.g. Moss et al. 1992) indicates that there have been three to five fold increases or more in sediment and nutrient exports from Queensland coastal catchments since European settlement. Further research in this area is being conducted through the Authority's Water Quality Program. At this stage there is compelling evidence to answer this question in the affirmative, at least for short-term events. While it is probable that nutrient loadings have been increased through human activities, there is very limited data to substantiate claims by some scientists that levels of nutrients are chronically elevated (e.g. Bell and Elmetri 1995). Short-term increases in nutrients associated with substantial run-off events are probable. Other natural events, such as upwelling of Coral Sea waters, contributes significant amounts of nutrients (phosphorus) to GBR waters in some areas at certain times.

- Does the level of nutrient increase result in increased food supplies for COTS larvae? (i.e. are the right sizes and species of phytoplankton affected?)

Laboratory work by Mr Ken Okaji at the AIMS suggests that increased nutrients favour disproportionate increases in the abundance of nanoplankton (> 2 μm) which is a critical component of larval COTS diets. However, in the field, phytoplankton blooms associated with major run-off events are generally only short-lived (lasting only two to three days) and the levels of nitrogen and phosphorus required to shift phytoplankton community structure is unknown.

Future Direction 9: *Further research is needed to confirm the food sources (in particular the sizes of phytoplankton) and dietary requirements of COTS larvae and to determine whether or not realistic elevated nutrient levels (i.e. those likely to be encountered in GBR waters) positively affect these in the field.*

- Do these increased nutrients (and their effects on food availability) extend to mid-shelf waters where COTS larval 'clouds' occur, and at times when the larvae are likely to be in the water column?

A number of research projects and direct observations of river plumes have confirmed the occasional extension of coastal influences to mid-shelf regions in the northern areas of the GBR. Evidence suggests that rainfall, current and winds affect the cross-shelf extent of river plumes. The timing and frequency of such major run-off events are unpredictable, as are COTS spawning events (although December appears to be the peak of effective spawning activity).

Future Direction 10: *Further research to determine the timing of peak COTS spawning and the environmental triggers responsible for initiating spawning activity is needed.*

Future Direction 11: *Monitoring and modelling (including hindcasting) the offshore extent of river and coastal runoff around COTS spawning times (December - January) as well as continued monitoring in the Cairns Section of the Marine Park to determine spatial and temporal fluctuations in key water quality parameters (including size-fractionated phytoplankton densities) is needed.*

- Does an increase in larval food supply result in significant increases in larval survival, shortening of larval life (which may translate into higher survival through shorter exposure to predation in the plankton) and/or more successful settlement of larvae?

Research by Mr Ken Okaji of AIMS has produced results opposed to earlier work conducted by Dr Randolf Olson who concluded that under normal conditions COTS larvae are unlikely to be food limited (Olson 1987). Additional laboratory experiments and measurement of chlorophyll concentrations in the field indicated that the growth and development of COTS larvae were food-limited under natural conditions. Most successful settlement of COTS larvae generally occurred when mean chlorophyll *a* levels were $> 0.5\text{-}0.8\ \mu g\ l^{-1}$. Okaji also noted considerable inter-annual variability in development rates and survival of COTS larvae in some experiments.

Future Direction 12: *Further research to establish whether or not larvae are normally food limited in the field is required. Additional studies are needed to establish whether or not short-term increases in food sources significantly enhance COTS larval survival and development.*

Future Direction 13: *Monitoring of size-fractionated chlorophyll concentrations in the suspected source area to assess the probability of COTS larvae encountering favourable conditions (where concentrations exceed the critical levels) should be continued.*

Unsuccessful attempts to rear COTS larvae and juveniles over the last few years have highlighted the inadequate status of knowledge on factors affecting reproduction and larval survival. Factors other than nutrition may play critical roles in larval development, survival and settlement. Information in this area is useful not only for understanding these key processes, but also as a precursor to developing efficient rearing techniques for the production of juveniles necessary for further predation studies.

> <u>Future Direction 14</u>: *Further research into factors (other than nutrition) affecting reproduction, larval development, survival and settlement is required.*

- Are outbreaks of COTS the result of enhanced survival of larvae?

There is a substantial difference between larval settlement and recruitment to the population. Small juvenile COTS have been shown to be exposed to intense predation pressure (Keesing and Halford 1992).

> <u>Future Direction 15</u>: *Research to establish the relative roles of pre- and post-settlement processes in limiting adult population densities is needed* (see next section on predation).

Results from research in a number of these areas will also provide information on possible connections between water quality and COTS outbreaks in the context of natural causes (e.g. Birkeland's 'terrestrial runoff hypothesis').

Predation

An answer to the question of whether or not human exploitation of the fish predators of COTS has caused or exacerbated recent outbreaks on the GBR requires the resolution of three primary questions:

(1) what are the COTS predators that may have been affected by fishing or collecting?
(2) has fishing or collecting by humans caused a significant decline in the abundance of these predators?
(3) has this reduction caused or exacerbated COTS outbreaks?

A study of the gut contents of putative fish predators of adult COTS on an outbreaking reef failed to find evidence of significant predation on COTS. Predation on juvenile COTS has been measured at one location but problems with rearing juveniles for these experiments resulted in the research being discontinued. As there are good reasons why predation on juvenile COTS should be more significant than at later stages, this work must be repeated when juveniles become available.

> <u>Future Direction 16</u>: *Larval and juvenile COTS rearing should be continued with a view to continuing research into predation on juvenile COTS. This research should focus on identifying principal predators and measuring predation rates on juvenile COTS in the field. Predation studies should be initiated as a matter of high priority if substantial populations of small juvenile COTS are detected in the field.*

One problematic area of predation on COTS involves the role of the giant triton (*Charonia tritonis*). Views on the significance of this known predator are diametrically opposed. Although giant tritons are the most frequently observed predator of large juveniles and adults, they are slow in consuming their prey (hence there is more opportunity for observations). Consumption rates of COTS by tritons (based on observations in artificial situations) suggest that they could be a significant predator. Population densities are unknown because of the cryptic nature of the species and their apparent rareness. The impact of collecting tritons from the GBR (prior to the banning of this activity in 1969) on population densities is also unknown. There is some evidence to suggest that tritons are attracted to aggregations of COTS and if this is so, this behaviour could be utilised to improve the cost-effectiveness of triton research.

Future Direction 17: *Research to establish the possible correlation between COTS and triton densities should be conducted when appropriate densities of COTS are located. If sufficient numbers of tritons are found, basic research (population densities, feeding preferences and rates, movements etc.) should be conducted.*

Analysis of historical information to address the question of fishing pressure proved fruitless because of inadequate and confused record keeping. The Authority's Effects of Fishing Program and research being conducted through the CRC Reef Research Centre are currently investigating the effects of line and inter-reef trawl fishing on target species and associated reef communities. Results of this research should provide information relevant to understanding the impacts of fishing on COTS predators in recent times but the historical trends will never be unravelled.

This part of the question hinges on understanding what is a significant reduction in predator densities. On the basis of modelling predation on COTS, Dr Hamish McCallum concluded that it was not possible to establish a minimum level that predation must reach to be of importance in preventing outbreaks. He also concluded that any increase in starfish mortality may decrease the intensity or frequency of outbreaks and any predator capable of increasing mortality by 0.01% per day was important. Such mortality estimates can be tested by experimental manipulations noted above (Direction 11).

Future Direction 18: *Close collaboration between the COTS Program and Effects of Fishing Programs should be maintained to ensure that information derived from research is relevant (where possible) to addressing the question of human impacts on COTS predators.*

Management Responses: Controls and Planning

Recent research into local COTS control techniques found chemicals that were effective in killing starfish but were more environmentally friendly than copper sulphate (the poison previously recommended). The alternative (100% sodium bisulphate or *Dry Acid*) is now being used in locally controlling COTS numbers in some areas of high tourism use on the GBR and overseas. A variety of control strategies based on the injection of poison and removal have been employed in the past. These have ranged from low-level (involving one or two divers) but frequent (daily or weekly) controls through to highly intensive operations (using teams of ten or more divers) months or years apart. The implementation of particular strategies has been based on convenience rather than an appreciation of effectiveness.

Future Direction 19: *Research to determine the most cost-effective strategies for locally controlling COTS outbreaks using injection of sodium bisulphate should be conducted.*

The conduct of effective local controls relies heavily on the early detection of outbreaks and the existence of established plans of action. Monitoring as described above should facilitate achievement of the former objective. A COTS Contingency Plan has been developed to provide guidelines for a rapid response to any future major outbreaks. However, the Plan focuses on the need to establish the extent of suspected outbreaks and aspects of communication between tourism operators and Reef management agencies. It doesn't describe detailed research initiatives required to take advantage of the early detection of outbreaks.

Future Direction 20: *A COTS Research Contingency Plan should be developed to provide a prioritised program of research to be initiated in the event of early detection of outbreaks. Priority should be given to work that needs to be done prior to, during and after outbreaks. Collection of surface sediments should be considered in this context.*

Public Information

The Reef-user survey scheme (COTSWATCH)

The COTSWATCH survey scheme is already proving highly successful. Since November 1993, GBRMPA have received an unprecedented number of completed survey forms. Indeed the Reef-user surveys have been instrumental in identifying the current increase in the number of COTS on some reefs between Cairns and Lizard Island. The feedback given to all contributors through public lectures and presentations as well as through the R&M Section's newsletter *Reef Research* is largely responsible for the high proportion of contributors to the COTSWATCH scheme now reporting their observations on a regular basis. This is particularly encouraging, because this kind of information will potentially provide important long-term data on the dynamics of COTS populations.

Future Direction 21: *Maintenance of the current high level of active promotion of the COTSWATCH scheme is crucial. The provision of training to particular tourist operators and QDEH would assist in the quality of information received and an ability to confirm unusually large populations would be beneficial.* [see #1 also]

Media Component

The COTSREC and the Authority recognise the important role the media plays in forming public opinion on the COTS issue. A comprehensive media strategy aiming to provide a balanced and factually correct view of the COTS phenomenon has been prepared.

Future Direction 22: *The effectiveness of the COTS media strategy should be monitored and modified as circumstances change or if deficiencies are found.*

Educational Materials

The production of quality educational materials for distribution to schools and the general public is a highly desirable yet often expensive means of keeping a potentially large audience informed. Currently available materials (i.e. booklet and video) will need to be updated in the near future.

Future Direction 23: *The production of new updated educational materials may need to be given a fairly high priority, particularly if the status of COTS on the GBR changes in the near future. Any such materials should consider the particular requirements and guidelines of educational institutions as identified during informal discussions with teachers and librarians. This should ensure that a highly professional and effective product is available.*

Displays at Aquaria and Zoos

The development and setting up of modern interactive displays in both aquaria and zoos have the potential of reaching very large audiences. However, development costs are typically very high.

Future Direction 24: *The high costs involved do not allow the Authority to fully fund any such ventures. However, the COTS Program should continue to encourage interested parties to consider development of such displays and offer assistance where appropriate.*

Other Areas

At its November 1993 meeting the COTSREC recommended three additional priority areas for research:

- development of an assay based on the monoclonal antibody technique aimed at field identification of COTS larvae;
- development of scientific standards for testing of hydrodynamic models; and
- modelling of COTS, corals and fish population dynamics and the effects of management action.

The first two of these are currently being addressed by research projects funded through the Program. The COTSREC has recommended a workshop be held to review relevant aspects of population modelling.

Future Direction 25: *A workshop be held to review modelling of COTS and coral interactions; COTS and potential predator population dynamics and coral recovery. The workshop should identify priorities in the area of modelling and information needs.*

ADMINISTRATION AND FINANCE

Total annual funding for the COTS Program and budget allocations for projects are given in table 1. All funds have been provided from the Commonwealth Government. Allocations to AIMS appear as a single item in table 1 but are broken down into individual tasks in table 2.

As well as funding from GBRMPA the Australian Institute of Marine Science has put considerable resources into the Study. Notional figures for each project are given in table 2. Most of this support comes in the form of ship-time, computing, staff and stores. The Institute also provides large amounts of specialised equipment (e.g. Remote Operated Vehicle, computers, spectrophotometers, freeze dryers) without charge. As well, it has paid for the visits of several scientists from overseas (e.g. Dr John Lawrence, University of South Florida) under its Visiting Investigator(s) Program.

As figure 5 shows, the total funding for the Program was initially high following the review by Professor Don Anderson but, with declining COTS outbreaks, Program funding also declined. This reduction was consistent with a recommendation of Dr Johannes in his 1992 review (see appendix 4). But as Johannes noted, 'one does not disband the army when the current war is over' and funding for COTS research and monitoring has been maintained (albeit at a lower level) despite waning of the issue. At the current time, the COTS Program funding is at its lowest level for more than ten years.

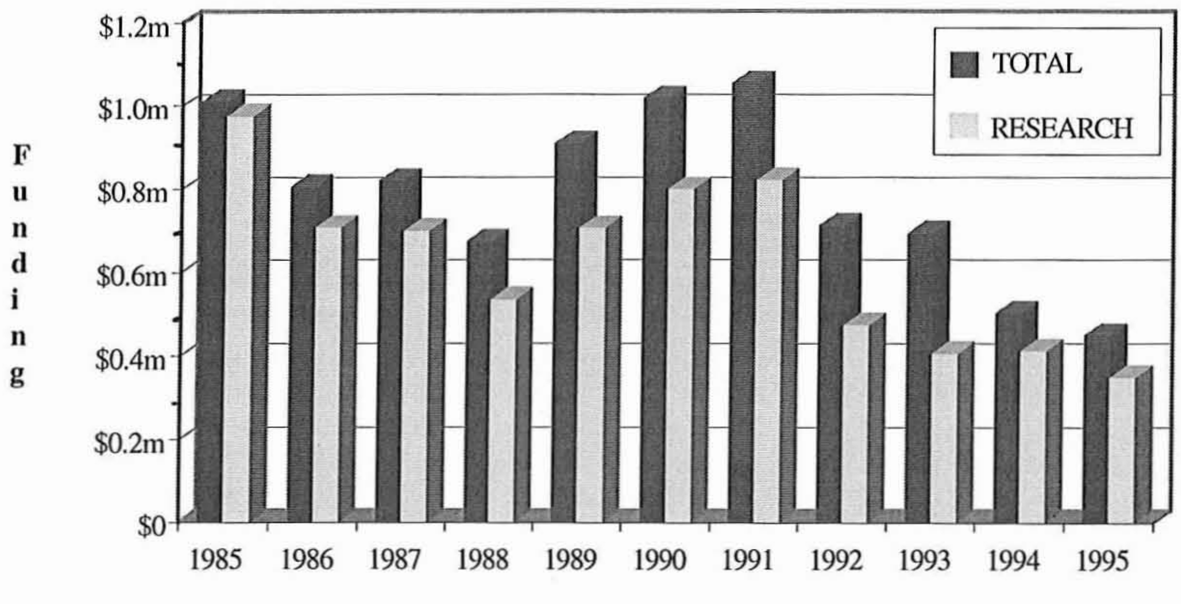

Figure 5. Total (research and monitoring) and research (only) funding for the GBRMPA COTS Program from the 1985-86 to 1995-96 financial years

Despite declining funds, the average cost of projects has remained relatively stable (figure 6). Allocation of funds to the seven priority research areas for the period of the COTSREC Program are shown in figure 7.

Cost Code	Description	89-90 ($)	90-91 ($)	91-92 ($)	92-93 ($)	93-94 ($)	94-95 ($)	TOTAL ($)
0612057	GBRMPA staff salaries	95 500	110 000	115 000	92 000	90 000	90 000	**592 500**
0612077	Travel & subsistence	20 000	20 000	18 179	18 000	9 525	9 500	**85 704**
0612094	COTSREC chair expenses	5 000	5 000	5 000	3 000	500	500	**19 000**
0612199	Incidentals	8 000	10 000	8 089	5 000	4 625	3 500	**39 714**
0612202	AIMS component	459 000	574 685	659 167	489 500	439 975	151 240*	**2 773 567**
0612204	Fiji COTS population dynamics	5 000	4 000		1 000	1 000	1 000	**12 000**
F10105	Remote sensing	3 032#						**3 032**
F10106	Pacific databases	5 000	4 000					**9 000**
F10108	COTS diseases	7 595#						**7 595**
0612210	Green Island COTS & Corals	23 000	27 430		23 000			**73 430**
F10111	North GBR sediments	8 500#						**8 500**
0612219	Mainland runoff	10 000						**10 000**
0612225	Aerial survey	3 000#						**3 000**
F10127	Survey comparisons	500#						**500**
F10128	Fish predators-catch	2 500#						**2 500**
F10130	Green Island pilot study	6 287#						**6 287**
F10133	Surface sediments	3 855#						**3 855**
F10134	Heron sediments	5 890#						**5 890**
F10136	South GBR sediments	1 860#						**1 860**
0612237	Massive corals	18 000	5 000	4 000				**26 000**
F10138	Predation anecdotes	2 000						**2 000**
F10139	Manta tow bias	11 500	27 889					**39 389**
F10140	Cairns survey	45 000						**45 000**
F10141	COTS & coral trout surveys	6 090						**6 090**
0612242	Age determination	33 750	41 000	21 200	6 900			**102 850**
F10143	Large scale models	36 000	30 000					**66 000**
0612244	Predation by fish	50 000	50 000	115 000	79 925	11 969		**306 894**
F10145	Tritons	10 000	5 000					**15 000**
0612246	Predation models	23 037	22 000					**45 037**
F10147	Fund raising	10 000						**10 000**
0612248	Bioerosion		15 000	18 000	15 000	6 850		**54 850**
0612249	Oceanography review		13 500	8 500				**22 000**
F10150	Geology Working Group		20 000					**20 000**
0612252	Monoclonal antibodies			6 000	7 000	16 375	14 500	**43 875**
0612253	1980s outbreak models			45 000				**45 000**
0612504	Hydrodynamic model test			20 000		20 000		**40 000**
F10155	Connectedness testing			5 500				**5 500**
0612301	COTS survey database					2 000		**2 000**
0612501	Backup rearing facility					42 250	64 000	**106 250**
	Education/Extension	6 000	11 000	7 000		8 000	11 000*	**43 000**
0612302	Local controls				4 000	12 000	12 750*	**28 750**
0612507	Green Island shoals survey					2 000		**2 000**
	GBRMPA Library					2 000		**2 000**
	Model standards					15 000	15 000	**30 000**
	Unallocated		34 893	408		5 500		**40 801**
0612513	Fine-scale surveys						90 000*	**90 000**
0612510	COTS population dynamics						36 645*	**36 645**
	Committed for next year			11 750				**11 750**
	TOTAL	**910 531**	**1 020 897**	**1 056 200**	**712 400**	**693 194**	**502 135**	**4 879 156**

Table 1. Funds allocated to projects under the Authority's COTSREC Program between the 1989-90 and 1994-95 fiscal periods

Footnotes:

\# final payments for projects initiated under the COTSARC Program
* funding from the CRC Reef Research Centre
\+ includes $30 000 from the CRC Reef Research Centre

Task No.	1989-90		1990-91		1991-92		1992-93		1993-94		1994-95		TOTAL
	GBRMPA	AIMS	GBRMPA	AIMS	GBRMPA	AIMS	GBRMPA	AIMS	GBRMPA	AIMS	GBRMPA	AIMS	
6.1.1	$203 123	$72 000	$220 221	$80 000	$233 425	$90 000	$239 000	$317 600	$286 553	$844 352			**$2 586 274**
6.1.2		$9 600											**$9 600**
6.1.3	$20 000	$35 690											**$55 690**
6.1.4	$4 000	$4 051		$4 216	$4 000	$4 207							**$20 474**
6.1.5	$67 271	$10 500	$93 639	$19 500	$94 800	$119 800	$89 000	$128 400					**$622 910**
6.1.6	$40 417		$105 727	$19 500	$116 850	$139 350	$33 000	$53 000					**$507 844**
6.1.7	$146 764	$39 871	$155 098	$51 717	$173 752	$57 495	$98 000	$24 615			$5 000		**$752 312**
6.2.1			$13 500	$115 394	$16 000	$115 078	$15 000	$119 322	$20 200	$16 500			**$430 994**
6.2.2			$10 000										**$10 000**
6.3.1					$20 500		$23 515		$32 841	$13 300	$28 920	$19 690	**$138 760**
6.3.2					$19 840	$35 300							**$55 140**
6.4.1							$6 000						**$6 000**
6.4.2							$9 250		$30 000	$7 200			**$46 450**
6.5.1									$61 833	$27 300	$87 320	$27 510	**$203 963**
6.5.2									$8 548	$14 800			**$29 348**
TOTAL	**$481 575**	**$171 712**	**$598 185**	**$290 327**	**$679 167**	**$561 230**	**$512 765**	**$642 937**	**$439 975**	**$923 452**	**$121 240**	**$47 200**	**$5 469 759**

Table 2. Funds and in-kind contributions allocated to tasks within the AIMS Crown-of-thorns Study between the 1989-90 and 1994-95 fiscal periods. Refer to table 3 for Task titles.

Footnotes:

a Support for Task 6.1.2 covered within Task 6.1.1.
b Funds for Task 6.1.4 in 1989-90 carried forward into 1990-91 because of delays in research.
c Funds for Task 6.2.1 in 1990-91 carried forward from previous financial year.
d Funds for Task 6.2.2 in 1990-91 included $5000 from previous financial year, and additional $5000 of GBRMPA unspent funds from previous year.
e Total allocation by GBRMPA in 1989-90 was $459 000; additional $16 000 support for L DeVantier and $6575 uncommitted funds.
f Total new allocation by GBRMPA in 1990-91 was $574 685; additional funds carried over from previous year.
g Total new allocation by GBRMPA in 1992-93 was $489 500; additional funds carried over from previous year.

Task Number	Task Title (Investigator)
6.1.1	Broadscale surveys of the crown-of-thorns starfish and its effects on corals along the Great Barrier Reef (P. Moran)
6.1.2	Surveys of juvenile crown-of-thorns starfish (P. Moran)
6.1.3	Analysis of coral colonies, populations and communities: interpretation of outbreak history and projection of recovery (T. Done)
6.1.4	Assessment of the utility of mitochondrial DNA as a genetic marker in crown-of-thorns starfish (*Acanthaster planci*) (J. Benzie)
6.1.5	The role of predation in factors influencing the survival of small juvenile *Acanthaster planci* cultured in the laboratory (J. Keesing)
6.1.6	Reproductive biology of the crown-of-thorns starfish (R. Babcock)
6.1.7	Project support and administration
6.2.1	Investigation of the trophodynamic implications of outbreaks of the crown-of-thorns starfish (D Klumpp and T. Hart)
6.2.2	Impact of crown-of-thorns starfish on interactions among space occupants of coral reefs: predictive models of coral reef community structure (C. Johnson)
6.3.1	Feeding ecology of early developmental stages of *Acanthaster planci* (K. Okaji)
6.3.2	Assessing the role of dissolved organic matter and bacteria in the nutrition and energetics of *Acanthaster planci* (T. Ayukai)
6.3.3	Assessing the utility of *Linckia* to test the connectedness of reefs with reference to *A. planci* dispersal (J. Benzie)
6.4.1	A preliminary study on the availability of dissolved organic matter to the nutrition of crown-of-thorns starfish larvae (T. Ayukai)
6.4.2	Proposal to develop DNA markers for *Linckia laevigata* and *Acanthaster planci* to test hydrodynamic models and trace larval dispersal (J. Benzie and S. Williams)
6.5.1	Improvement of the rearing technique for the larvae and juveniles of crown-of-thorns starfish (T. Ayukai and C. Cartwright)
6.5.2	Significance of river runoff to the nutrient and plankton dynamics in the Cairns-Cooktown region: crown-of-thorns starfish perspective (T. Ayukai)

Table 3. AIMS Task numbers, titles and investigators

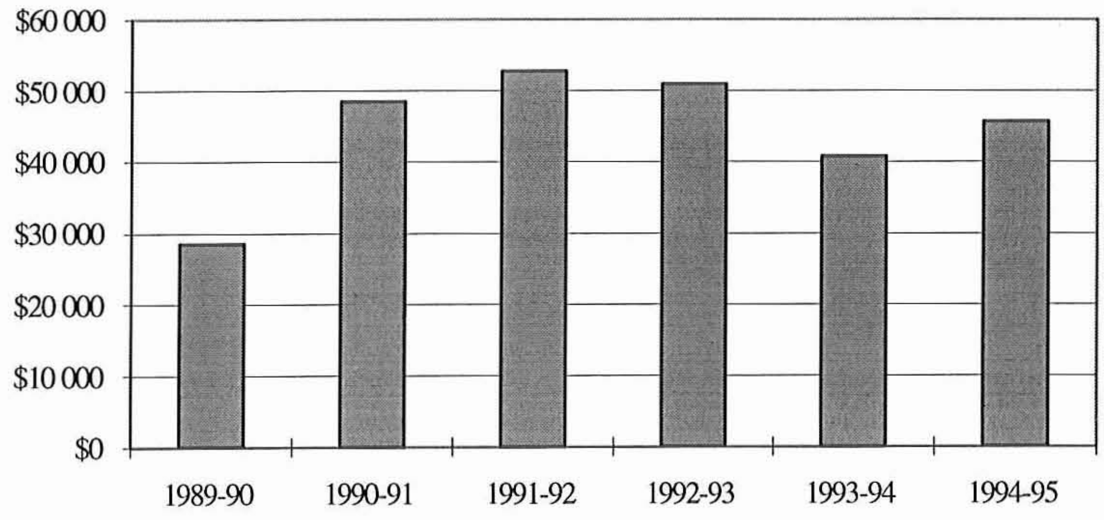

Figure 6. Average project cost over the duration of the COTSREC Program

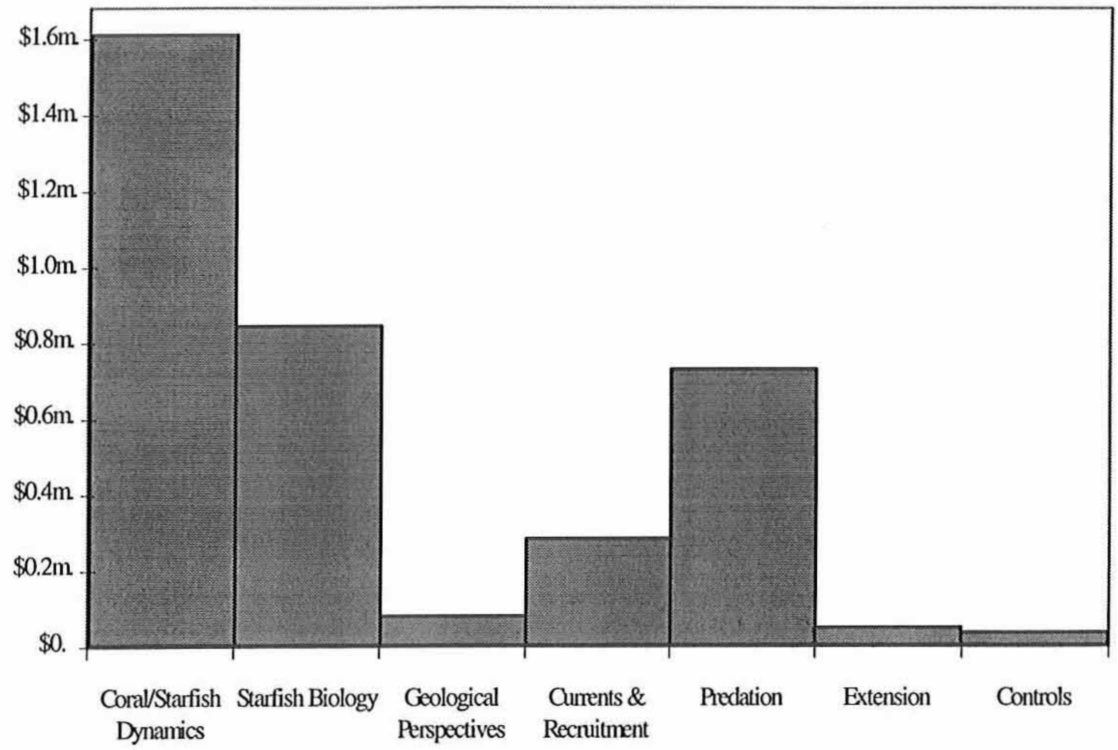

Figure 7. Allocation of funds to Program areas over the period July 1989 to June 1995

REFERENCES *(not cited in Publications listing)*

Anderson, D. T. 1989, A report to the Minister for the Arts, Sport, the Environment, Tourism and Territories, Senator the Honourable Graham Richardson, 59pp.

Bell, P. R. F. and Elmetri, I. 1995, Ecological indicators of large-scale eutrophication in the Great Barrier Reef lagoon, *Ambio*, 24(4): 208-215.

Birkeland, C. 1982, Terrestrial runoff as a cause of outbreaks of *Acanthaster planci* (Echinodermata: Asteroidea), *Mar. Biol.*, 69: 175-185.

Kenchington, R. A. 1977, Growth and recruitment of *Acanthaster planci* (L.) on the Great Barrier Reef, *Biol. Conserv.*, 11: 103-118.

Lassig, B. 1991, Final report on results of COTSAC management related research: December 1985 to June 1989, Research Publication, Great Barrier Reef Marine Park Authority, Townsville, 49pp.

Lucas, J. S. 1973, Reproductive and larval biology of *Acanthaster planci* (L.) in Great Barrier Reef waters, *Micronesica*, 9: 197-203.

Moran, P. J. 1986, The *Acanthaster* phenomenon, *Oceanogr. Mar. Biol.*, 24: 379-480.

Moran, P. J. and Johnson, D. B. 1990, Final report of the results of the COTSAC ecological research: December 1985 - June 1989, Crown-of-thorns Study Report 11, Australian Institute of Marine Science, Townsville, 40pp.

Moss, A. J., Rayment, G. E., Reilly, N. and Best, E. K. 1992, A preliminary assessment of sediment and nutrient exports from Queensland coastal catchments, Queensland Department of Environment and Heritage and Queensland Department of Primary Industries, January 1992.

Olson R. R. 1987, In situ culturing as a test of the larval starvation hypothesis for the crown-of-thorns, *Acanthaster planci*, *Limnol. Oceanogr.*, 32: 895-904.

Sano, M., Shimizu, M. and Nose Y. 1987, Long-term effects of destruction of hermatypic corals by *Acanthaster planci* infestation on reef fish communities at Iriomote Island, Japan, *Mar. Ecol. Prog. Ser.*, 37: 191-199.

Steven, A. 1988, An analysis of fishing activities on possible predators on the crown-of-thorns starfish (*Acanthaster planci*) on the Great Barrier Reef, Draft Final Report to the Great Barrier Reef Marine Park Authority, February 1988, 131 pp.

Williams, D. McD. 1986, Temporal variation in the structure of reef slope fish communities (central Great Barrier Reef): short term effects of *Acanthaster planci* infestation, *Mar. Ecol. Prog. Ser.*, 28: 157-164.

Zann, L. P. and Moran, P. J. 1988, A coordinated research program on the *Acanthaster* phenomenon in Australia, *Inter. Coral Reef Symp.*, 6: 117-182.

REPORTS AND PUBLICATIONS

The following reports and papers are based on research conducted with financial support (in part or full) through the Authority's COTSREC Program and from the AIMS crown-of-thorns Study. The list does not include Progress Reports to the Authority. Some studies were commenced prior to the COTSREC Program (in most cases with funding through the COTSARC Program), but all reports and papers were published between July 1989 and June 1995.

Australian Institute of Marine Science 1990, Report of field surveys of juvenile crown-of-thorns starfish, Final Report to the Great Barrier Reef Marine Park Authority, March 1990, 23 pp.

Antonelli, P. L. 1990, Applied Volterra-Hamilton systems of Finsler type: increased species diversity as a non-chemical defence for coral against crown-of-thorns, In: Bradbury, R. H. (ed.), *Acanthaster and the coral reef: a theoretical perspective*, Springer-Verlag, Berlin, pp. 220-235.

Antonelli, P. L., Bradbury, R. H., Buck, R. G., Elliott, R. J. and Reichelt, R. E. 1990, Nonlinear prediction of crown-of-thorns outbreaks on the Great Barrier Reef, In: Bradbury, R. H. (eds.), *Acanthaster and the coral reef: a theoretical perspective*, Springer-Verlag, Berlin, pp. 314-328.

Antonelli, P. L, Bradbury, R. H., Hammond, L. S., Ormond, R. F. G. and Reichelt, R. E. 1990, The *Acanthaster* phenomenon: a modelling approach - Rapporteurs; Report, In: Bradbury, R. H. (ed.), *Acanthaster and the coral reef: a theoretical perspective*, Springer-Verlag, Berlin, pp. 329-338.

Antonelli, P. L, Kazarinoff, N. D., Reichelt, R. E., Bradbury, R. H. and Moran, P. J. 1990, A diffusion-reaction transport model for large-scale waves in crown-of-thorns starfish outbreaks on the Great Barrier Reef, In: Bradbury, R. H. (ed.), *Acanthaster and the coral reef: a theoretical perspective*, Springer-Verlag, Berlin, pp. 45-53.

Ayling, A. M. and Ayling, A. L. 1989, Crown-of-thorns and coral trout density on three Central Section reefs: 1983-1989, GBRMPA Research Publication No. 15, June 1992, Great Barrier Reef Marine Park Authority, Townsville, 54 pp.

Ayling, A. M. and Ayling, A. L. 1991, Discussion of the methodological problems associated with estimates of *Acanthaster planci* (crown-of-thorns starfish) density on the Great Barrier Reef, Final Report to the Great Barrier Reef Marine Park Authority, August 1991, 11 pp.

Ayukai, T. 1993, Resource availability to the larvae of crown-of-thorns starfish in Great Barrier Reef waters: an overview, In: Engelhardt, U. and Lassig, B. (eds.), *The possible causes and consequences of outbreaks of the crown-of-thorns starfish*, Workshop Series No. 18, Great Barrier Reef Marine Park Authority, Townsville, pp. 21-36.

Ayukai, T. 1994, Ingestion of ultraplankton by the plankton larvae of the crown-of-thorns starfish *Acanthaster planci*, *Biol. Bull.*, 186: 90-100.

Ayukai, T. and Hoegh-Guldberg, O. 1992, Assessment of the role of dissolved organic matter and bacteria in the nutrition of crown-of-thorns starfish larvae, Final Report to the Great Barrier Reef Marine Park Authority, May 1992, 52 pp.

Ayukai, T., Sturmey, H. and Swann, L. 1993, A preliminary study on the availability of dissolved organic matter to the nutrition of crown-of-thorns starfish larvae, Final Report to the Great Barrier Reef Marine Park Authority, December 1993, 19 pp.

Babcock, R. C. 1990, Spawning behaviour of *Acanthaster planci*, *Coral Reefs* 9: 124.

Babcock, R. C. 1992, Reproductive biology, spawning and field fertilization rates of *Acanthaster planci*, *Aust. J. Mar. Freshwater Res.*, 43: 525-534.

Babcock, R. C. and Mundy, C. N. 1992, Seasonal changes in fertility and fecundity in *Acanthaster planci*, *Proc. 7th Inter. Coral Reef Symposium*, 2: 757-761.

Babcock, R. C. and Mundy, C. N. 1993, Reproductive biology of the crown-of-thorns starfish *Acanthaster planci*, Final Report to the Great Barrier Reef Marine Park Authority, November 1993, 56 pp.

Babcock, R. C. and Mundy, C. N. 1993, Seasonal changes in fertility and fecundity in *Acanthaster planci*, In: Engelhardt, U. and Lassig, B. (eds.*), The possible causes and consequences of outbreaks of the crown-of-thorns starfish*, Workshop Series No. 18, Great Barrier Reef Marine Park Authority, Townsville, pp. 13-20.

Babcock, R. C., Mundy, C. N., Keesing, J. K., and Oliver, J. 1992, Predictable and unpredictable spawning events: in situ behavioural data from free-spawning coral reef invertebrates, *Invertebrate Reproduction and Development*, 22: 213-228.

Babcock, R. C., Mundy, C. N., and Whitehead, D. 1994, Sperm diffusion models and in situ confirmation of long-distance fertilization in the free-spawning asteroid *Acanthaster planci*, *Biol. Bull.*, 186: 17-28.

Baker, V. J., Bass, D. K., Christie, C. A., Johnson, D. D., Miller, I. R., Miller-Smith, B. A., Moran, P. J. and Thompson, A. A. 1990, Broadscale surveys of crown-of-thorns starfish on the Great Barrier Reef 1989 to 1990, The Crown-of-thorns Study, Australian Institute of Marine Science, Townsville, 204 pp.

Baker, V. J., Bass, D. K., Christie, C. A., Miller, I. R., Miller-Smith, B. A. and Thompson, A. A. 1991, Broadscale surveys of crown-of-thorns starfish on the Great Barrier Reef 1990 to 1991, The Crown-of-thorns Study, Australian Institute of Marine Science, Townsville, 170 pp.

Baker, V. J., Moran, P. J., Mundy, C. N. Reichelt, R. E. and Speare, P. J. 1991, A guide to the reef ecology database, 1. Description of data. The Crown-of-thorns Study, Australian Institute of Marine Science, Townsville, 48 pp.

Bainbridge, S., Bass, D. K. and Miller, I. R. 1994, Broadscale surveys of crown-of-thorns starfish and corals on the Great Barrier Reef 1992 to 1993, The Long-term Monitoring Project, Australian Institute of Marine Science, Townsville, 131 pp.

Bass, D. K., Davidson, J., Johnson, D. B., Miller-Smith, B. A. and Mundy, C. N. 1989, Broadscale surveys of crown-of-thorns starfish on the Great Barrier Reef 1987 to 1988, The Crown-of-thorns Study, Australian Institute of Marine Science, Townsville, 172 pp.

Bass, D. K., Davidson, J., Johnson, D. B., Miller, I. R., Miller-Smith, B. A. and Mundy, C. N. 1989, Broadscale surveys of crown-of-thorns starfish on the Great Barrier Reef 1988 to 1989, The Crown-of-thorns Study, Australian Institute of Marine Science, Townsville, 166 pp.

Bass, D. K. and Miller, I. R. 1994, Broadscale surveys of crown-of-thorns starfish and corals on the Great Barrier Reef 1992 to 1993, The Crown-of-thorns Study, Australian Institute of Marine Science, Townsville, 131 pp.

Benzie, J. A. H. 1990, Techniques for the electrophoresis of crown-of-thorns starfish (*Acanthaster planci*) enzymes, The Crown-of-thorns Study, Australian Institute of Marine Science, Townsville, 27 pp.

Benzie, J. A. H. 1990, Genetic relationships of crown-of-thorns starfish, In: Done, T. J. and Navin, K. F. (eds.) *Vanuatu marine resources: report of a biological survey*, Australian Institute of Marine Science, Townsville, pp. 114-117.

Benzie, J. A. H. 1992, Review of the genetics, dispersal and recruitment of crown-of-thorns starfish (*Acanthaster planci*), *Aust. J. Mar. Freshwater Res.*, 43(3): 597-610.

Benzie, J. A. H. 1992, Assessment of the utility of mitochondrial DNA as a genetic marker in crown-of-thorns starfish (*A. planci*), Final Report to the Great Barrier Reef Marine Park Authority, May 1992, 8 pp.

Benzie, J. A. H. 1993, Assessment of the utility of *Linckia* to rest connectedness of reefs with reference to *A. planci* dispersal, Final Report to the Great Barrier Reef Marine Park Authority, March 1993, 9 pp.

Benzie, J. A. H., Black, K. P., Moran, P. J. and Dixon, P. 1994, Small-scale dispersion of eggs and sperm of the crown-of-thorns starfish (*Acanthaster planci*) in a shallow coral reef habitat, *Biol. Bull.*, 186: 153-167.

Benzie, J. A. H. and Dixon, P. 1994, The effects of sperm concentration, sperm:egg ratio, and gamete age on fertilization success in crown-of-thorns starfish (*Acanthaster planci*) in the laboratory, *Biol. Bull.*, 186: 139-152.

Black, K. P. 1992, The temperatures and water currents of the Great Barrier Reef during crown-of-thorns starfish outbreaks since 1966, Final Report to the Great Barrier Reef Marine Park Authority, October 1992, 55 pp.

Black, K. P. 1995, Numerical predictions of the initiation and progression of crown-of-thorns starfish outbreaks, Final Report to the Great Barrier Reef Marine Park Authority, January 1995, 12 pp. + appendices.

Black, K. P. and Gay, S. L. 1990, Reef-scale numerical hydrodynamic modelling developed to investigate crown-of-thorns starfish outbreaks, In: Bradbury, R. H. (ed.), *Acanthaster and the coral reef: a theoretical perspective*, Springer-Verlag, Berlin, pp. 120-150.

Black, K. P., and Gay, S. L. 1990, A numerical scheme for determining trajectories in particle models, In: Bradbury, R. H. (ed.) *Acanthaster and the coral reef: a theoretical perspective*, Springer-Verlag, Berlin, pp. 151-156.

Black, K. P., Gay, S. L. and Andrews, J. C. 1990, Residence times of neutrally-buoyant matter such as larvae, sewage, or nutrients on coral reefs, *Coral Reefs*, 9: 105-114.

Black, K. P., Greilach, P. and Hatton, D. 1991, Calibration of a numerical model of the central Great Barrier Reef on a 2.25km grid, VIMS Technical Report No. 12, May 1991, 27 pp. + 12 figs.

Black, K. P. and Moran P. J. 1991, Influence of hydrodynamics on the passive dispersal and initial recruitment of larvae of *Acanthaster planci* (Echinodermata: Asteroidea) on the Great Barrier Reef, *Mar. Ecol. Prog. Ser.*, 69: 55-65.

Black, K. P., Moran, P., Burrage, D., and De'ath, G. 1993, Are the hydrodynamics guilty of causing or stimulating outbreaks of crown-of-thorns starfish on the Great Barrier Reef ? In: Engelhardt, U. and Lassig, B. (eds.), *The possible causes and consequences of outbreaks of the crown-of-thorns starfish*, Workshop Series No. 18, Great Barrier Reef Marine Park Authority, Townsville, pp. 95-102.

Bode, L., Dight, I. J. and James, M. K. 1992, Modelling approach to hydrodynamics and the large-scale dispersal of *Acanthaster planci*, Final Report to the Great Barrier Reef Marine Park Authority, January 1992, 33 pp.

Brodie, J. E. 1992, Enhancement of larval and juvenile survival and recruitment in *Acanthaster planci* from the effects of terrestrial runoff: a review, *Aust. J. Mar. Freshwater Res.*, 43(3): 539-554.

Bradbury, R. H. (ed.) **1990,** *Acanthaster* and the coral reef: a theoretical perspective, Springer-Verlag, Berlin, 338 pp.

Bradbury, R. H. and Antonelli, P. L. 1990, What controls outbreaks? In: Bradbury, R. H. (ed.), *Acanthaster and the coral reef: a theoretical perspective*, Springer-Verlag, Berlin, pp. 278-290.

Bradbury, R. H. van der Laan, J. D. and Macdonald, B. 1990, Modelling the effects of predation and dispersal on the generation of waves of starfish outbreaks, *Mathl. Comput. Modelling*, 13: 61-67.

Bradbury, R. H. and Mundy, C. N. 1989, Large scale shifts in the biomass of the Great Barrier Reef ecosystem, In: Sherman, K. and Alexander, L. (eds.) *Biomass and geography of large marine ecosystems*, Boulder: Westview, pp. 143-167.

Burrage, D. M., Black, K. P. and Ness, K. F. 1994, Long-term current prediction in the central Great Barrier Reef, *Continental Shelf Res.*, 14: 803-829.

Cameron, A. M., Endean, R. and DeVantier, L. M. 1991, The effects of *Acanthaster planci* predation on two species of massive coral, *Hydrobiologia*, 216/217: 257-262.

Cameron, A. M., Endean, R. and DeVantier, L. M. 1991, Predation on massive corals: are devastating outbreaks of *Acanthaster planci* novel events? *Mar. Ecol. Prog. Ser.*, 75: 251-258.

Dale, M. B., Bradbury, R. H. and Reichelt, R. E. 1990, Reef syntax: an exploratory data analysis of the *Acanthaster* phenomenon using strings and grammars, In: Bradbury, R. H. (ed.), *Acanthaster and the coral reef: a theoretical perspective*, Springer-Verlag, Berlin, pp. 54-71.

De'ath, G. 1992, Sightability as an indicator of bias in manta tow surveys of *Acanthaster planci*: comment on Fernandes, Marsh, Moran and Sinclair, *Coral Reefs,* 11: 119-121.

DeVantier, L. M. 1994, The structure of assemblages of massive corals in the central Great Barrier Reef: An assessment of the effects of predation by *Acanthaster planci* (L.), The University of Queensland, Brisbane PhD thesis, 223 pp. + appendices.

DeVantier, L. M. and Deacon, J. 1990, Distribution of *Acanthaster planci* at Lord Howe Island, the southern-most Indo-Pacific reef, *Coral Reefs*, 9: 145-148.

Dight, I. J. and James, M. K., Bode, L. and Stewart, L. 1991, Modelling approach to hydrodynamics and the large-scale larval dispersal of *Acanthaster planci*: Sensitivity analyses, Department of Civil and Systems Engineering Research Report CS 41, James Cook University of North Queensland.

Dight, I. J., Bode, L. and James, M. K. 1990, Modelling the larval dispersal of *Acanthaster planci*: I. Large scale hydrodynamics, Cairns Section, Great Barrier Reef Marine Park, *Coral Reefs*, 9: 115-123.

Dight, I. J., Bode, L. and James, M. K. 1990, Modelling the larval dispersal of *Acanthaster planci*: II. Patterns of reef connectivity, *Coral Reefs*, 9: 125-134.

Done, T. J. 1990, Transition matrix models, crown-of-thorns and corals, In: Bradbury, R. H. (ed.), *Acanthaster and the coral reef: a theoretical perspective*, Springer-Verlag, Berlin, pp. 291-297.

Done, T. J. and DeVantier, L. M. 1990, Fundamental change in coral community structure at Green Island, *Coral Reefs*, 9: 166.

Done, T. J., DeVantier, L. M., Fisk, D. A. and van Woesik, R. 1992, Regional and local patterns of coral recovery on reefs affected by crown-of-thorns starfish: central Great Barrier Reef, Final Report to the Great Barrier Reef Marine Park Authority, December 1992, 46 pp.

Engelhardt, U. and Lassig, B. (eds.) **1992,** Crown-of-thorns starfish - Research Update 1991/92, Great Barrier Reef Marine Park Authority, January 1992, 19 pp.

Engelhardt, U. and Lassig, B. (eds.) **1993,** The possible causes and consequences of outbreaks of the crown-of-thorns starfish, Proceedings of a workshop held in Townsville, Australia, 10 June 1992, Workshop Series No. 18, Great Barrier Reef Marine Park Authority, Townsville, 168 pp.

Fernandes, L. 1990, Effect of the distribution and density of benthic target organisms on manta tow estimates of their abundance, *Coral Reefs*, 9: 161-165.

Fernandes, L. 1991, Development of a more robust method for determining the status of individual reefs with respect to outbreaks of crown-of-thorns starfish (*Acanthaster planci*), Final Report to the Great Barrier Reef Marine Park Authority, April 1991, 47 pp.

Fernandes, L., Marsh, H., Moran, P. J. and Sinclair, D. 1990, Bias in manta tow surveys of *Acanthaster planci*., *Coral Reefs*, 9: 155-160.

Fernandes, L., Marsh, H. and Sinclair, D. 1992, Manta tow counts as indices of the distribution and abundance of *Acanthaster planci*: a reply to De'ath, *Coral Reefs*, 11: 179-181.

Fisk, D. A. 1990, An integrated study of hard coral regeneration and juvenile crown-of-thorns starfish at Green Island, Final Report to the Great Barrier Reef Marine Park Authority, January 1990, 17 pp.

Fisk, D. A. 1990, The distribution of juvenile crown-of-thorns at Green Island, Final Report to the Great Barrier Reef Marine Park Authority, March 1990, 7 pp.

Fisk, D. A. 1991, An integrated study of hard coral regeneration and juvenile crown-of-thorns dynamics at Green Island, Final Report to the Great Barrier Reef Marine Park Authority, November 1991, 12 pp.

Fisk, D. A. 1992, Recruitment of *Acanthaster planci* over a five-year period at Green Island Reef, *Aust. J. Mar. Freshwater Res.*, 43(3): 629-633.

Fisk, D. A. 1993, Six years of hard coral recovery following *Acanthaster planci* predation at Green Island (1985-1990), Final Report to the Great Barrier Reef Marine Park Authority, March 1993, 97 pp.

Fisk, D. A. 1993, Hard coral regeneration at Green Island - Status in March 1993, Final Report to the Great Barrier Reef Marine Park Authority, November 1993, 17 pp. + figs.

Fisk, D. A. and Harriott, V. J. 1990, Spatial and temporal variation in coral recruitment on the Great Barrier Reef - implications for dispersal hypotheses, *Mar. Biol.*, 107: 485-490.

Gay, S. L, Andrews, J. C. and Black, K. P. 1990, Dispersal of neutrally-buoyant material near John Brewer Reef, In: Bradbury, R. H. (ed.), *Acanthaster and the coral reef: a theoretical perspective*, Springer-Verlag, Berlin, pp. 95-119.

Gladstone, W. 1992, Observations of crown-of-thorns starfish spawning, *Aust. J. Mar. Freshwater Res.*, 43 (3): 535-538.

Gladstone, W. 1993, The history of crown-of-thorns starfish controls on the Great Barrier Reef and an assessment of future needs for controls, In: Engelhardt, U. and Lassig, B. (eds.), *The possible causes and consequences of outbreaks of the crown-of-thorns starfish*, Workshop Series No. 18, Great Barrier Reef Marine Park Authority, Townsville, pp. 147-156.

Hart, T. 1993, Long-term response of herbivorous fish to crown-of-thorns starfish outbreaks (*Abstract only*), In: Engelhardt, U. and Lassig, B. (eds.), *The possible causes and consequences of outbreaks of the crown-of-thorns starfish*, Workshop Series No. 18, Great Barrier Reef Marine Park Authority, p. 131.

Hoegh-Guldberg, O. 1993, Is *Acanthaster planci* able to utilise dissolved organic matter (DOM) to satisfy the energetic requirements of larval development? In: Engelhardt, U. and Lassig, B. (eds.), *The possible causes and consequences of outbreaks of the crown-of-thorns starfish*, Workshop Series No. 18, Great Barrier Reef Marine Park Authority, pp. 37-54.

Hoegh-Guldberg, O. 1994, Uptake of dissolved organic matter by the larval stages of the crown-of-thorns starfish *Acanthaster planci*, *Mar. Biol.*, 120: 55-63.

James, M. K. and Scandol, J. P. 1992, Larval dispersal simulations: correlation with the crown-of-thorns starfish outbreaks database, *Aust. J. Mar. Freshwater Res.*, 43 (3): 569-582.

Johnson, C. 1992, Reproduction, recruitment and hydrodynamics in the crown-of-thorns phenomenon on the Great Barrier Reef: introduction and synthesis, *Aust. J. Mar. Freshwater Res.*, 43 (3): 517-523.

Johnson, C. (ed.) **1992,** Crown-of-thorns starfish on the Great Barrier Reef: Reproduction, recruitment and hydrodynamics, Papers from a symposium on crown-of-thorns phenomenon, held on 22-23 May 1991 in Townsville, Australia, CSIRO, 146 pp. (*reprint of Aust. J. Mar. Freshwater Res. 43(3)*).

Johnson, C. 1992, Settlement and recruitment of *Acanthaster planci* on the Great Barrier Reef: questions of process and scale, *Aust. J. Mar. Freshwater Res.*, 43(3): 611-627.

Johnson, C. and Preece, A. 1993, Consequences of outbreaks: relationships between spatial scales of outbreaks and temporal scales of recovery (*Abstract only*), In: Engelhardt, U. and Lassig, B.

(eds.), *The possible causes and consequences of outbreaks of the crown-of-thorns starfish*, Workshop Series No. 18, Great Barrier Reef Marine Park Authority, p. 129.

Johnson, C. R. and Preece, A. L. 1993, Recovery of model coral communities: complex behaviours from interaction of parameters operating at different spatial scales, *In: Complex Systems: From Biology to Computation*, D. G. Green and T. Bossomaier (eds.), IOS Press, Amsterdam, pp. 69-81.

Johnson, C. R. and Preece, A. L. 1992, Damage, scale and recovery in model coral communities: the importance of system state, *Proc 7th Inter. Coral Reef Symposium,* 1: 606-615.

Johnson, C. R. and Sutton, D. C. 1994, Bacteria on the surface of crustose coralline algae induce metamorphosis of the crown-of-thorns starfish *Acanthaster planci, Mar. Biol.*, 120: 305-310.

Johnson, C. R., Sutton, D. C. Olson, R. R. and Giddins, R. 1991, Settlement of crown-of-thorns starfish: the role of bacteria on surfaces of coralline algae and a hypothesis for deepwater recruitment, *Mar. Biol. Prog. Ser.*, 71: 143-162.

Johnson, D. B., Moran, P. J. and Driml, S. 1990, Evaluation of a crown-of-thorns starfish (*Acanthaster planci*) control program at Grub Reef (central Great Barrier Reef), *Coral Reefs*, 9: 167-171.

Johnson, L. G. and Babcock, R. C. 1994, Temperature and the larval ecology of the crown-of-thorns starfish, *Acanthaster planci, Biol. Bull.*, 187: 304-308.

Keesing, J. K. 1990, Feeding biology of the crown-of-thorns starfish, *Acanthaster planci* (Linnaeus), James Cook University of North Queensland, Townsville, PhD thesis, 197 pp.

Keesing, J. K. 1992, A comparative study of mortality patterns of juvenile coral reef starfish in Japan and Australia, Report to DITAC, July 1992, 7 pp.

Keesing, J. K. 1992, Influence of persistent sub-infestation *Acanthaster planci* (L.) and high density *Echinometra mathaei* (de Blainville) populations on coral reef community structure in Okinawa, Japan, *Proc. 7th Inter. Coral Reef Symposium,* 1: 769-779.

Keesing, J. K. 1993, The role of predation in factors influencing the survival of small juvenile *Acanthaster planci* cultured in the laboratory, Final Report to the Great Barrier Reef Marine Park Authority, June 1993, pp. 111.

Keesing, J. K., Bradbury, R. H. DeVantier, L. M. Riddle, M. J. and De'ath, G. 1992, The geological evidence for recurring outbreaks of the crown-of-thorns starfish: a reassessment from an ecological perspective, *Coral Reefs*, 11: 79-85.

Keesing, J. K., Cartwright, C. M., and Hall, K. C. 1993, Measuring settlement intensity of echinoderms on coral reefs, *Mar. Biol.*, 117: 399-407.

Keesing, J. K. and Halford, A. R. 1992, The importance of post-settlement processes for the population dynamics of *Acanthaster planci* (L.), *Aust. J. Mar. Freshwater Res.*, 43: 635-651.

Keesing, J. K. and Halford, A. R. 1992, Field measurement of survival rates of juvenile *Acanthaster planci* (L.): techniques and preliminary results, *Mar. Ecol. Prog. Ser.*, 85: 107-114. (Reprinted in: Engelhardt, U. and Lassig, B. (eds.), *The possible causes and consequences of outbreaks of* *the crown-of-thorns starfish*, Workshop Series No. 18, Great Barrier Reef Marine Park Authority, pp. 57-70.)

Keesing, J. K. and Lucas, J. S. 1992, Field measurement of feeding and movement rates in the crown-of-thorns starfish, *Acanthaster planci* (L.), *J. Expt. Mar. Biol. Ecol.*, 156: 89-104.

Kelleher, G. 1993, A management approach to the COTS question, In: Engelhardt, U. and Lassig, B. (eds.), *The possible causes and consequences of outbreaks of the crown-of-thorns starfish*, Workshop Series No. 18, Great Barrier Reef Marine Park Authority, pp. 157-160.

Kelleher, G. and Lassig, B. R. 1993, Targeting species for research: A government perspective, In: Moritz, C. and J. Kikkawa (eds.), *Conservation Biology in Australia and Oceania*, Surrey Beatty & Sons, Chipping Norton, pp. 219-223.

Lassig, B. R. 1993, The need for a crown-of-thorns starfish contingency plan, In: Engelhardt, U. and Lassig, B. (eds.), *The possible causes and consequences of outbreaks of the crown-of-thorns starfish*, Workshop Series No. 18, Great Barrier Reef Marine Park Authority, Townsville, pp. 161-168.

Lassig, B. R. 1995, Controlling crown-of-thorns starfish, Great Barrier Reef Marine Park Authority Publication, April 1995, 11 pp.

Lassig, B. R. 1995, Planning for crown-of-thorns starfish population increases, Great Barrier Reef Marine Park Authority Publication, April 1995, 15 pp.

Lassig, B. R. and Engelhardt, U. 1994, Crown-of-thorns starfish: Another outbreak looms, *Search*, 25(3): 66-68.

Lassig, B. R., Gladstone, W., Moran, P. and Engelhardt, U. 1993, A crown-of-thorns starfish contingency plan, *Proc. 7th Inter. Coral Reef Symposium*, 2: 780-788.

Lassig, B. R. and Kelleher, G. 1991, Crown-of-thorns starfish on the Great Barrier Reef, Environmental Research in Australia III - Case Studies: 39-62, ASTEC, Canberra, Australia.

Lovell, E. R. 1994, The crown-of-thorns starfish in Fiji, Final Report to the Great Barrier Reef Marine Park Authority, September 1994, 31 pp.

Marine BioLogic 1991, Survey of marine scientists and other experts for anecdotal observations of crown-of-thorns predation, Final Report to the Great Barrier Reef Marine Park Authority, January 1991, 49 pp.

McCallum, H. I. 1992, Effects of immigration on chaotic population dynamics, *J. theor. Biol.*, 154: 277-284.

McCallum, H. 1992, Completing the circle: stock-recruitment relationships and *Acanthaster*, *Aust. J. Mar. Freshwater Res.*, 43(3): 653-662.

McCallum, H. 1993, Are crown-of-thorns starfish populations chaotic? Would it matter if they were? In: Engelhardt, U. and Lassig, B. (eds.), *The possible causes and consequences of outbreaks of the crown-of-thorns starfish*, Workshop Series No. 18, Great Barrier Reef Marine Park Authority, Townsville, pp. 83-94.

McCallum, H. 1994, Modelling to assess the impact of predation on *Acanthaster planci*, Final Report to the Great Barrier Reef Marine Park Authority, Townsville, 93 pp.

Moran, P. J. and De'ath, G. 1992, Suitability of the manta tow technique for estimating relative and absolute abundance of crown-of-thorns starfish (*Acanthaster planci* L.) and corals, *Aust. J. Mar. Freshwater Res.*, 43(3): 357-378.

Moran, P. J. and De'ath, G. 1992, Estimates of the abundance of crown-of-thorns starfish (*Acanthaster planci*) on reefs within the Great Barrier Reef: the concept of outbreaking and non-outbreaking populations, *Mar. Biol.*, 113: 509-515.

Moran, P. J., De'ath, G., Baker, V. J., Bass, D. K., Christie, C. A., Johnson, D. B., Miller, I. R., Miller-Smith, B. A., Mundy, C. N. and Thompson, A. A. 1991, Broadscale surveys of crown-of-thorns starfish and corals along the Great Barrier Reef: 1982-1990. The Crown-of-thorns Study, Australian Institute of Marine Science, Townsville, 33 pp.

Moran, P. J., De'ath, G., Baker, V. J., Bass, D. K., Christie, C. A., Miller, I. R., Miller-Smith, B. A. and Thompson, A. A. 1992, Pattern of outbreaks of crown-of-thorns starfish (*Acanthaster planci* L.) along the Great Barrier Reef since 1966, *Aust. J. Mar. Freshwater Res.*, 43(3): 555-568.

Moran, P. J., De'ath, G., Baker, V. J., Bass, D. K., Christie, C. A., Miller, I. R. and Thompson, A. A. 1993, Broadscale surveys of crown-of-thorns starfish on the Great Barrier Reef 1982 to 1992, The Crown-of-thorns Study, Australian Institute of Marine Science, Townsville, 36 pp.

Moran, P. J. and Johnson, D. B. 1990, Final Report on the results of COTSAC ecological research: December 1985 - June 1989, Crown-of-thorns Study Report 11, Australian Institute of Marine Science, Townsville, 40 pp.

Moran, P. J., Johnson, D. B., Miller-Smith, B. A. Mundy, C. N. , Bass, D. K., Davidson, J., Miller, I. R. and Thompson, A. A. 1989, A guide to the AIMS manta tow technique, The Crown-of-thorns Study, Australian Institute of Marine Science, Townsville, 20 pp.

Mundy, C. N. 1990, Field and laboratory investigations of the line intercept transect technique for monitoring the effects of the crown-of-thorns starfish, *Acanthaster planci*, The Crown-of-thorns Study, Australian Institute of Marine Science, Townsville, 42 pp.

Mundy, C., Babcock, R. Ashworth, I. and Small, J. (*in press*), A portable discrete-sampling submersible plankton pump, *Biol. Bull.*

Musso, B. M. 1992, Rates of skeletal degradation following death in three species of *Acropora*, *Proc 7th Inter. Coral Reef Symposium*, 1: 413-418.

Musso, B. 1993, Effects of *Acanthaster* predation on bioerosion: design and preliminary results, In: Engelhardt, U. and Lassig, B. (eds.), *The possible causes and consequences of outbreaks of the crown-of-thorns starfish*, Workshop Series No. 18, Great Barrier Reef Marine Park Authority, Townsville, pp. 133-146.

Okaji, K. 1993, In situ rearing of crown-of-thorns larvae (*Abstract only*), In: Engelhardt, U. and Lassig, B. (eds.), *The possible causes and consequences of outbreaks of the crown-of-thorns starfish*, Workshop Series No. 18, Great Barrier Reef Marine Park Authority, Townsville, p. 55.

Oliver, J., De'ath, G., Done, T., Williams, D., Furnas, M. and Moran, P. (eds.) **1995,** Long-term monitoring of the Great Barrier Reef: Status Report Number 1, Australian Institute of Marine Science, 121 pp.

Ormond, R., Bradbury, R. H., Bainbridge, S., DeVantier, L. M., Fabricius, K., Keesing, J. K., Medlay, P. and Steven, A. 1990, Test of a model of regulation of crown-of-thorns starfish by fish predators, In: Bradbury, R. H. (ed.), *Acanthaster. A modelling approach*, Springer-Verlag, Berlin, pp. 180-207.

Paterson, J., 1990, Preliminary survey of Giant Triton (*Charonia tritonis*) on selected reefs in the Cairns Region (Hastings, Saxon, Norman reefs) during January 1990, Final Report to the Great Barrier Reef Marine Park Authority, April 1990, 20 pp.

Rasmussen, C. 1994, Anthropogenic disturbance of environmental signals retained in massive corals, James Cook University of North Queensland, Townsville. PhD thesis, 214 pp. + appendices.

Rasmussen, C., Cuff, C. and Hopley, D. 1992, Evidence of anthropogenic disturbances retained in the skeleton of massive corals from Australia's Great Barrier Reef, *Proc 7th Inter. Coral Reef Symposium*, 1: 201-210.

Reichelt, R. E. 1990, Dispersal and control models of *Acanthaster planci* populations on the Great Barrier Reef, In: Bradbury, R. H. (ed.), *Acanthaster* and the coral reef: a theoretical perspective, Springer-Verlag, Berlin, pp. 6-16.

Reichelt, R. E., Bradbury, R. H. and Moran, P. J. 1990, The crown-of-thorns starfish, *Acanthaster planci*, on the Great Barrier Reef, *Mathl. Comput. Modelling*, 13: 45-60.

Reichelt, R. E., Bradbury, R. H. and Moran, P. J. 1990, Distribution of *Acanthaster planci* outbreaks on the Great Barrier Reef between 1966 and 1989, *Coral Reefs*, 9: 97-103.

Reichelt, R. E., Greve, W., Bradbury, R. J. and Moran, P. J. 1990, *Acanthaster planci* outbreak initiation: a starfish-coral site model, *Ecol. Modell.*, 49: 153-177.

Scandol, J. P. 1993, *CotSim*: Scientific visualisation and gaming simulation for the *Acanthaster* phenomenon, In: Engelhardt, U. and Lassig, B. (eds.), *The possible causes and consequences of outbreaks of the crown-of-thorns starfish*, Workshop Series No. 18, Great Barrier Reef Marine Park Authority, Townsville, pp. 119-128.

Scandol, J. P. and James, M. K. 1992, Hydrodynamics and larval dispersal: a population model of *Acanthaster planci* on the Great Barrier Reef, *Aust. J. Mar. Freshwater Res.*, 43(3): 583-596.

Scandol, J. P. and James, M. K. 1992, Fitting a population model of *Acanthaster planci* to the results of broadscale surveys of the Great Barrier Reef, *Proc 7th Inter. Coral Reef Symposium*, 2: 789-796.

Stump, R. 1992, Survey of *Acanthaster planci* (L.) on Suva Reef, Fiji, and comparison of morphometric relationships with data from an outbreak population on Davies Reef, Great Barrier Reef, Final Report to GBRMPA, June 1992, 15 pp. + 9 figs.

Stump, R. 1993, Life history characteristics of *Acanthaster planci* (L.) populations - potential clues to outbreaks, In: Engelhardt, U. and Lassig, B. (eds.), *The possible causes and consequences of outbreaks of the crown-of-thorns starfish*, Workshop Series No. 18, Great Barrier Reef Marine Park Authority, Townsville, pp. 105-114.

Stump, R. 1995, Age determination and life history characteristics of *Acanthaster planci* (L.) (Echinodermata: Asteroidea), James Cook University of North Queensland, Townsville, PhD thesis, 400 pp.

Stump, R. J. W. and Lucas, J. S. 1990, Linear growth in spines from *Acanthaster planci* (L.) involving growth lines and periodic pigment bands, *Coral Reefs*, 9: 149-154.

Sweatman, H. P. A. 1995a, A field study of fish predation on juvenile crown-of-thorns starfish, *Coral Reefs*, 14: 47-53.

Sweatman, H. P. A. 1995b, Feeding studies on potential fish predators of post-settlement *Acanthaster planci*, Draft Final Report to the Great Barrier Reef Marine Park Authority, 1995, 76 pp. + appendices.

Sweatman, H. and Butler, I. 1993, An experimental investigation of the ability of adult crown-of-thorns starfish to survive physical damage, In: Engelhardt, U. and Lassig, B. (eds.), *The possible causes and consequences of outbreaks of the crown-of-thorns starfish*, GBRMPA Workshop Ser. No. 18, pp. 71-82.

Young, I. R., Black, K. P. and Heron, M. L. 1993, Circulation in the ribbon reef region of the Great Barrier Reef, *Continental Shelf Res.*, 14: 117-142.

Zann, L. 1993, Some perspectives on the *Acanthaster* phenomenon (*Abstract only*), In: Engelhardt, U. and Lassig, B. (eds.), *The possible causes and consequences of outbreaks of the crown-of-thorns starfish*, Workshop Series No. 18, Great Barrier Reef Marine Park Authority, Townsville, p. 103.

Zann, L., Brodie, J. and Vuki, V. 1990, History and dynamics of the crown-of-thorns starfish *Acanthaster planci* (L.) in the Suva area, Fiji, *Coral Reefs*, 9: 135-144.

Zann, L. and Vuki, V. 1992, Monitoring the recruitment of *Acanthaster planci* and community changes on Suva Reef and adjacent reefs, Se Viti Levu, Fiji Group: 1991 Survey, Final Report to COTSREC, February 1992, 18 pp.

APPENDIX 1

COMPILATION OF THE MAJOR FINDINGS AND RECOMMENDATIONS OF PROFESSOR D. T. ANDERSON'S REVIEW OF THE CROWN-OF-THORNS STARFISH RESEARCH PROGRAM

1. The current management policy of the Great Barrier Reef Marine Park Authority for crown-of-thorns starfish control is soundly based and takes account of current knowledge of crown-of-thorns starfish populations on the Great Barrier Reef. The policy could be applied more extensively only if special funds were made available for this purpose.

2. The Authority has promoted appropriate research into crown-of-thorns management under the COTSAC research program and has fully evaluated the results of this research in relation to its current management policy. The causes of outbreaks of crown-of-thorns starfish are still unknown.

3. Ecological research and management-related research under the COTSAC program both support the view that local control techniques are available and could be effective, even though expensive, but large scale control or eradication is impracticable and unaffordable.

4. The COTSAC research program indicates that population fluctuations of the crown-of-thorns starfish have occurred in the past, but the scale of such fluctuations cannot be analysed in detail. The present phenomenon appears to have a long history.

5. The COTSAC research program has been defined, reviewed and operated in an efficient and productive manner, within the limits allowed by annual funding. A high degree of dedication is evident among the research workers and research managers involved in the program.

6. The provision of Federal funds for the COTSAC program on an annual basis has disadvantaged the program in various ways, primarily through the imposition of a need for rapid decision making and the corollary that the review committee for the program (COTSARC) has been unduly constrained by time considerations. Despite this, COTSARC has carried out its task as effectively as possible.

7. The COTSAC research program had led to significant advances in the understanding of the ecology of the crown-of-thorns starfish. As a result of this program, opportunities have now been created to investigate the broadscale ecology of the species in the Great Barrier Reef more deeply, and to better analyse its reproduction, dispersal, settlement and recruitment processes. Understanding of the causes and management of the crown-of-thorns starfish depends critically on the outcome of this research. Areas of future research should include:

* predation at all levels;
* population dynamics;
* effects of human activities, including agricultural runoff and fisheries; and
* biological control.

8. The research would benefit from an injection of supplementary research workers with suitable skills, especially in experimental biology. This could be obtained through four to five suitable post-doctoral appointments guaranteed for three years, and is critical to progress in the investigation of predation and population dynamics.

9. The crown-of-thorns starfish research program on the Great Barrier Reef should be continued for another three to five years at a dedicated and committed funding level of at least AUS$1 million a year.

10. For the GBRMPA to run the program effectively, it needs the support of a review committee that could be active in determining the initial funding and annual renewal of all projects. Composition of the committee should include Professor Swan, two experts from GBRMPA, two experts from AIMS and three external (Australian-based) experts.

11. The review committee should meet at least three times each year, to review applications of funds, to receive and deliberate upon the reports of assessors on these applications, and to review progress of the program before the next round of applications.

12. In order to maintain a flow of information about the program to the wider community, Professor Swan should also be asked to chair a coordinating committee. This committee, meeting annually, could be informed about the progress of the program with a view to allowing input from other interest groups (e.g. tourism and state government). If comprised of two members of the scientific review committee and four members chosen from the Great Barrier Reef Consultative Committee (GBRCC), the coordinating committee could report to the GBRCC annually on the research program.

13. A full time coordinator of the program should be appointed. This person would need to be ex officio a member of the scientific review committee and the coordinating committee. In anticipation of a continuation of a major part of the research program at AIMS, and the obvious need for coordination of this component within AIMS, THE GBRMPA appointed coordinator would need to work closely with the responsible staff member(s) at AIMS.

14. The facilities and expertise of the Australian Institute of Marine Science are essential to the completion of the ecological research now required, but control of the program should remain with the Great Barrier Reef Marine Park Authority.

15. All projects funded under the COTS research program should carry contractual obligations, including strict identification of the application of the funds within the project and an annual report of the progress to the GBRMPA.

APPENDIX 2

MEMBERS OF THE CROWN-OF-THORNS STARFISH RESEARCH COMMITTEE (COTSREC)

Professor J. M. Swan (Chair) to January 1992
Professor Graham Mitchell (Chair) from January 1992
Dr J. T. Baker OBE (Director, AIMS) to December 1992
Dr Meryl Williams (Director, AIMS) from May 1993 to December 1993
Dr Peter Moran (AIMS COTS Study Leader) to May 1993, then as Acting Director, AIMS from February 1994
Professor Peter Davies (BMR) to August 1993
Professor David Hopley (JCU) from September 1993
Professor Ray Golding (Vice Chancellor, JCU)
Professor Graeme Kelleher (Chairman, GBRMPA)
Dr Brian Lassig (GBRMPA)
Dr Tenshi Ayukai (AIMS) from May 1993 to April 1995
Mr Robert Pearson (QDPI)
Dr Keith Sainsbury (CSIRO)
Professor Chris Crossland (Director, CRC Reef Research Centre) from March 1994.

Dr William Gladstone (Secretariat; GBRMPA) to December 1991
Mr Udo Engelhardt (Secretariat; GBRMPA) from January 1992

APPENDIX 3

TERMS OF REFERENCE FOR THE CROWN-OF-THORNS STARFISH RESEARCH COMMITTEE (COTSREC)

Background

The Crown of Thorns Starfish Advisory Committee (COTSAC) established by the Great Barrier Reef Marine Park Authority (GBRMPA) in 1984 noted that establishment and coordination of a program of research relevant to particular GBRMPA needs would best be achieved with the guidance of an advisory committee appointed by GBRMPA for this specific task. It recommended that the advisory committee should report directly to GBRMPA and should liaise with research institutions in Australia and overseas.

In December 1988 the Minister for the Arts, Sport, the Environment, Tourism and Territories, Senator the Honourable Graham Richardson, called for a review of aspects of the research program recommended by the COTSAC.

The review, conducted by Professor D. T. Anderson, Challis Professor of Biology in the University of Sydney, made recommendations for improving mechanisms for defining, reviewing and operating the COTSAC research program. Professor Anderson concluded the GBRMPA needed the 'support of a review committee that could be active in determining the initial funding and annual renewal of all projects within the program'. COTSREC is intended to provide that support.

Terms of Reference

(1) Membership

The Committee shall comprise:

Chairperson
Two Representatives from the Australian Institute of Marine Science
Two Representatives from the Great Barrier Reef Marine Park Authority
A Senior Representative from James Cook University of North Queensland
Four External Experts[(a)]

The Committee may appoint Corresponding Members[(b)] to be kept informed of progress in the research program and to be routinely consulted on technical matters relevant to their areas of expertise.

The Committee may also nominate external consultants to complement the areas of expertise represented by Committee members. These consultants should be asked to review elements of the program relevant to their areas of expertise and report their assessments to COTSREC to assist the Committee's funding deliberations and reviews of program directions. As necessary, these individual consultants may be invited to join COTSREC meetings.

(a) External experts should be selected on one or more of the following criteria:
- Active involvement in relevant research;
- Wide acceptability of their scientific expertise in *Acanthaster* research, tropical marine biology, experimental design, statistics or modelling;
- Experience in analogous marine or terrestrial research/management programs.

(b) Corresponding members may be invited to attend COTSREC meetings from time to time.

The Committee may consult with other Australian and overseas experts on an ad hoc basis when required.

(2) Objectives

COTSREC is an advisory committee to GBRMPA, in relation to crown-of-thorns starfish issues primarily research, funding and public information.

Within guidelines established by the Authority and subject to available funds, the Committee shall meet at least three times each year to:

i. review applications for funds for crown-of-thorns starfish research;
ii. review and deliberate upon the reports of assessors on these applications;
iii. review the progress of the crown-of-thorns starfish research program before the next round of applications;
iv. advise GBRMPA on research priorities and patterns of expenditure within the crown-of-thorns starfish research program;
v. advise on a program for keeping the public informed on the crown-of-thorns starfish phenomenon and research and management actions which are being undertaken in relation to it; and
vi. advise GBRMPA on the implications of crown-of-thorns starfish research for management of the GBR Marine Park.

COTSREC should arrange to meet annually with the GBR Consultative Committee to report on the research program.

(3) Procedures

i. The positions on COTSREC, other than Chairperson, are honorary.
ii. The Chairperson will receive a fee of up to $5000 p.a.
iii. All approved expenses incurred in the conduct of COTSREC business will be met by GBRMPA.
iv. The Chairperson may exercise Executive Powers to recommend to GBRMPA transfer of funds (on recommendations of the research program Coordinator) up to $5000 for any one project and up to $50 000 overall in any one period between meetings. The Chairperson will refer all recommendations made under these Executive Powers to the next meeting of COTSREC for endorsement of actions taken.
v. Procedures at meetings will be determined by the Committee.

APPENDIX 4

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS OF 'A REVIEW OF THE CROWN-OF-THORNS STARFISH RESEARCH PROGRAM: 1989-1991' BY DR R. E. JOHANNES

1. The COTS research program has operated in an efficient and productive manner during 1989-91 and has contributed significantly to the knowledge required for the use and enjoyment of the Great Barrier Reef in an ecologically sustainable manner. However, because of uncertainty over funding, some research projects started later than planned.

2. Significant additional progress is assured in the 1991-92 fiscal year, and continued support for the program into this third year is essential.

3. Some activities in the COTSREC program have the potential to contribute significantly to research in important areas outside the immediate scope of the program, including research on fisheries stocks and recruitment and on water quality.

4. The COTS monitoring program is providing exceptionally useful information. It is the key to identifying outbreaks rapidly and monitoring their spread, impact and decline. It also provides information essential to many other COTS research projects. Steps should be taken to guarantee funding of the COTS monitoring program at no less than the current (indexed) level of support at least until the cause(s) of outbreaks are known. The monitoring program should be reviewed regularly.

5. The COTS research program should also continue beyond the 1991-92 year, but at a level of support that reduces over a period of three years to fund a core program (as distinct from monitoring) of about half of the current (indexed) level. This program should be reviewed in three years.

6. The existing monitoring working group involving GBRMPA and AIMS should be responsible for reviewing the COTS monitoring program. This group should consider certain modifications to the monitoring program and report its conclusions to COTSREC before the end of 1991.

7. The GBRMPA COTS staff should be requested by COTSREC to develop, in consultation with researchers, contingency plans for research and funding to be activated in the event of a new COTS outbreak. Conclusions should be reported to COTSREC at the Committee's next meeting and the plan reviewed at each COTSREC meeting.

8. A contingency fund of $400 000 should be sought from the Federal Government to be held in a trust fund and made available for core research in the event of an outbreak in the future. The fund should be used only when COTSREC and GBRMPA decide that an outbreak has clearly occurred.

9. Research on monoclonal antibodies and settling tubes should be given greater support.

10. No new research on COTS in the sedimentary record should be supported (other than, perhaps, modest pilot studies) unless new techniques show promise of characterising the dynamics of pre-1960 outbreaks with sufficient precision to challenge rigorously the hypothesis that human activities have caused or enhanced recent outbreaks. Proposals for research in this area could continue to be accepted and reviewed.

11. Support for hydrodynamic modelling should be phased out until existing model predictions have been field tested.

12. Screening and coordination of requests from researchers for assistance from the AIMS monitoring team should be undertaken by a group including the AIMS Project Manager, a member of the survey team and the GBRMPA Program Coordinator. Any problems with assessing priorities and resolving conflicts should be directed to the COTSREC Chairman.

13. COTSREC should provide and enforce guidelines for addressing COTSREC objectives in proposals and reports.

14. COTSREC should continue to review its funding priorities in order to reduce still further the number of projects supported.

APPENDIX 5

GBRMPA POLICY ON COTS CONTROLS

'Broadscale control of crown-of-thorns starfish is not to be attempted in the Great Barrier Reef Marine Park unless human activity is proven to cause or exacerbate outbreaks, or unless any future outbreaks are much more extensive and intensive than the two that have been observed.

Local control of crown-of-thorns starfish (by any method involving treatment of individual starfish) must be consistent with zoning plan provisions and should be consistent with management plan provisions.*

Recognising the potentially high risks associated with biological and chemical control measures in complex coral reef environments, research into biological and chemical control of crown-of-thorns starfish should not be supported other than in identifying potential agents whose application in consistent with the two policies above.

In the event of a causal relationship between human activity and crown-of-thorns starfish outbreaks being established, the Authority should use all its powers and influence to regulate that activity to minimise the effects of that activity on crown-of-thorns starfish populations, and should also seek to minimise the effects of outbreaks.

* *Note: A permit will be required for local control measures in General Use A and B Zones where it is desired to collect more than five starfish per person in any 28-day period. A permit may be granted for local control measures in higher protection areas (MNPA and B, Conservation Park, Buffer and National Park Zones) where the provisions allow for the taking of animals that pose a threat to ecosystems or the use and amenity of an area.'*

APPENDIX 6

A MANAGEMENT APPROACH TO THE COTS QUESTION*

Graeme Kelleher
Great Barrier Reef Marine Park Authority
PO Box 1379, Townsville QLD 4810

* Extracted from GBRMPA Workshop Series No. 18 (1993) 'The possible causes and consequences of outbreaks of the crown-of-thorns starfish'. U. Engelhardt and B. Lassig (eds). GBRMPA, Townsville, Qld.

Abstract

Scientists and managers often view issues from different perspectives. Scientists as a group have traditionally wished to learn more about an issue for the sake of learning, for the sake of testing a hypothesis, for the sake of furthering their careers or for a combination of these reasons. While managers are also curiosity driven, they are usually required to focus their curiosity on those aspects of matters which are vital to the solution of management problems. From the manager's perspective, the fundamental question to be answered about the COTS phenomenon is whether or not it has been grossly affected by human activity. On the basis of the answer to that question, the manager will determine his response, particularly whether or not to interfere in the 'natural' system or to refrain from interference. The logic of this position is discussed.

The Authority's policy on controlling COTS is not to interfere on a large scale unless it can be shown that outbreaks are caused or exacerbated by human activity. However local controls are initiated to protect sites of particular value to tourism or science. Every scientific review of this matter has supported our policy.

Many people adopt one of two fundamentally different explanations for why crown-of-thorns populations suddenly increase dramatically. One is that the phenomenon is entirely 'natural'. That is, it is not affected by human activity. The other is that it is entirely human-induced.

Of course, bearing in mind the pervasive effect that human activity is having on the world's biosphere, it is quite likely that the truth is a mixture of these two views, that is, that crown-of-thorns infestations are affected to some degree by human activity. We don't however, know whether this is so, and if it is, whether human activity is contributing to the intensity, frequency or extent of the phenomenon positively or negatively.

The Authority recognises that long-term protection of the Reef ecosystem is the primary reason for the existence of the Authority and for everything that we do. Therefore we approach the crown-of-thorns issue from the perspective of risk.

We know that the animal is a natural inhabitant of the Reef and that is has been around for millennia. We know, therefore, that the Reef as we know and cherish it has developed in the presence of the starfish. That is not to say that there have always been recurrent population explosions, but there may have been. The primary question is: should we undertake widespread and massive destruction of crown-of-thorns starfish whenever there is a primary outbreak?

What are the risks and benefits of non-interference? Clearly, an immediate benefit is the saving of an enormous amount of money. Experience has shown that it costs up to $35 per starfish to kill large numbers of them using the best methods identified so far - copper sulphate injections (Johnson et al. 1990). Since there can be millions of starfish on a single reef, the people of Australia stand to save much more than the annual budget of the Authority by not embarking on massive starfish killing programs.

What are the risks? At the start of both recent starfish infestations we were told that, if the starfish numbers were not controlled, the entire GBR ecosystem would be at risk, with the possibility of a major phase-shift from a coral-dominated community to something else, with massive erosion of the existing reef structure and the adjacent mainland. In fact, thorough surveys have shown that in the last major wave of infestations starting in 1979 and evidently petering out now, only $17 \pm 4\%$ of all the 2900 or so reefs of the GBR were affected visibly by infestations and only about one third of these (i.e. 6% of all of the GBR reefs) were seriously affected. It is hard to believe that permanent damage to the Reef ecosystem could be caused by an event of only this magnitude.

The conclusions from this last experience therefore are that very significant economic benefits accrued from the 'non-interference' policy and that the risks from applying that policy were small.

What about the risks and benefits of applying a policy of massive starfish destruction programs? The benefits have to be conjectural because we cannot be sure that very large populations could be controlled. However I suppose we could assume that the number of reefs seriously affected by the starfish could have been reduced from the 6% that were so affected. But it's not so easy to argue that this is a benefit. Many people have conjectured that crown-of-thorns infestations might be beneficial to reefs in ways similar to the effect of bushfires on some Australian native forests. So perhaps there would have been no benefits.

There would have been great costs, however. Even if only Green Island Reef had been subject to starfish destruction action, the costs would have been many millions of dollars. Further, there is the possibility that our massive interference in what might be a natural element of the Great Barrier Reef system could have major unforeseen ecological effects. I would count such effects as costs because we value the Reef for what it is naturally, not for what human interference might make it. Further still, it is at least conceivable that such an action focussing on Green Island might have shortened the time for the next outbreak or created a chronic elevated crown-of-thorns population state as has occurred in the Ryukyu Islands (Birkeland and Lucas 1990).

The conclusion is that the risks from adopting a policy of massive destruction of crown-of-thorns starfish are very significant and that the only potential benefits may turn out to be costs in the long run.

In contrast, no long-term risks to the whole GBR are identified in not interfering massively with infestations, unless they are much more extensive and intensive that the two that have been observed. In such a case, the Authority would definitely reconsider its policy. If, for instance, it appeared that 30% of all the reefs of the system were to be seriously affected, then I would be asking the Government for the resources to attempt population control.

This explains why the Authority has maintained the policy of not undertaking massive starfish killing programs. However, I should explain why we do encourage or cooperate in protecting small reef areas that are important for tourism or research. Again, the reasoning is based on benefits and costs. We can in such cases identify very clearly the economic benefits of protecting such reef areas. The costs are limited to the costs of killing comparatively few starfish. There is no risk that this small amount of human interference could have a significant unforeseen effect on the whole Reef ecosystem. So the benefits clearly outweigh the costs, both those that are identifiable and those that can be classified only in risk terms.

References

Birkeland, C. and Lucas, J. S. 1990, *Acanthaster planci*: Major management problem of coral reefs, CRC Press, Boca Raton, 257pp.

Johnson, D. B., Moran, P. J. and Driml, S. 1990, Evaluation of a crown-of-thorns starfish (*Acanthaster planci*) control program at Grub Reef (central Great Barrier Reef), *Coral Reefs*, 9: 167-171.